

Observational Constraints on the Catastrophic Disruption Rate of Small Main Belt Asteroids

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ABSTRACT

We have calculated 90% confidence limits on the steady-state rate of catastrophic disruptions of main belt asteroids in terms of the absolute magnitude at which one catastrophic disruption occurs per year (H_0^{CL}) as a function of the post-disruption increase in brightness (Δm) and subsequent brightness decay rate (τ). The confidence limits were calculated using the brightest unknown main belt asteroid ($V = 18.5$) detected with the Pan-STARRS1 (Pan-STARRS1) telescope. We measured the Pan-STARRS1’s catastrophic disruption detection efficiency over a 453-day interval using the Pan-STARRS moving object processing system (MOPS) and a simple model for the catastrophic disruption event’s photometric behavior in a small aperture centered on the catastrophic disruption event. We then calculated the H_0^{CL} contours in the ranges from $0.5 \text{ mag} < \Delta m < 20 \text{ mag}$ and $0.001 \text{ mag d}^{-1} < \tau < 10 \text{ mag d}^{-1}$ encompassing measured values from known cratering and disruption events and our model’s predictions. Our simplistic catastrophic disruption model suggests that $\Delta m \sim 20 \text{ mag}$ and $0.01 \text{ mag d}^{-1} \lesssim \tau \lesssim 0.1 \text{ mag d}^{-1}$ which would imply that $H_0 \gtrsim 28$ — strongly inconsistent with $H_{0,B2005} = 23.26 \pm 0.02$ predicted by Bottke *et al.* (2005) using purely collisional models. However, if we assume that $H_0 = H_{0,B2005}$ our results constrain $11.0 \text{ mag} \lesssim \Delta m \lesssim 12.4 \text{ mag}$, inconsistent with our simplistic impact-generated catastrophic disruption model. We postulate that the solution to the discrepancy is that $> 99\%$ of main belt catastrophic disruptions in the size range to which this study was sensitive ($\sim 100 \text{ m}$) are not impact-generated, but are instead due to fainter rotational breakups, of which the recent discoveries of disrupted asteroids P/2013 P5 and P/2013 R3 are probable examples. We estimate that current and upcoming asteroid surveys may discover up to 10 catastrophic disruptions/year brighter than $V = 18.5$.

Subject headings: Surveys:Pan-STARRS; Asteroids; Disruptions, Collisions

1. Introduction

The ever-increasing survey discovery rate of asteroids and comets has revealed a Solar System teeming with activity. We now understand the Solar System in terms of inter-related, evolving small body populations whose orbital element and size-frequency distributions (SFDs) are sculpted by gravitational interactions with the giant planets, and by other forces such as the Yarkovsky and YORP effects (Bottke *et al.* 2006). These interactions can scatter small bodies to different regions of the Solar System or eject them entirely.

The main belt SFD has been shaped by collisions between asteroids, most effectively by ‘catastrophic’ collisions that disrupt an asteroid into a ‘family’ containing thousands of fragments. Parker *et al.* (2008) estimate that at least 35% of large asteroids ($H < 13$) and 50% of smaller bodies are members of a collisional family. Other mechanisms for SFD modification include but are not limited to: rotational breakup, sublimation of water ice and other volatiles, thermal instability, and electrostatic forces. A new class of ‘active asteroids’ (*e.g.* Hsieh and Jewitt 2006; Jewitt 2012) is comprised of dynamically-ordinary main belt objects (expected to be inert) that display cometary behavior for weeks or even years due to these mechanisms.

A catastrophic disruption is conventionally defined as a breakup of an asteroid that leaves no fragment larger than half the original mass (Greenberg *et al.* 1978). Traditionally this has been understood to occur via a collision between a parent body and a smaller projectile body. Current understanding of catastrophic disruptions is limited by the rarity of these events and by a preference toward investigation of impacts between kilometer-scale and larger objects that result in the creation of asteroid families (*e.g.* Michel *et al.* 2002). These studies have focused on the macroscopic properties of asteroid collisions with less emphasis on the microscopic aspects of the resulting dust production and dispersion.

Furthermore, while cometary dust behavior has been studied for many decades, building upon models by Finson and Probst (1968) that describe the orbits of dust grains using radiation pressure and solar gravity, the behavior of dust generated in asteroidal outburst events has only recently begun to be studied in detail (*e.g.* Agarwal *et al.* 2013; Bodewits *et al.* 2011; Stevenson *et al.* 2012).

Bottke *et al.* (2005) employed collisional-cascade simulations (CoDDEM; also *e.g.* Durda *et al.* 1998; O’Brien and Greenberg 2003) to predict a main belt steady-state impact-generated catastrophic disruption rate of about one event per year for objects of 100 m diameter¹. In these simulations, the main belt is divided into logarithmic size bins, and the population within each bin evolves over time according to the number of objects lost due to *e.g.* disruption, cratering events, and dynamic depletion that are, in turn, gained by bins corresponding to smaller asteroid sizes. They incorporate estimated rates for the dynamical depletion of the main belt in the early Solar System due to perturbations from planetary embryos and a newly-formed Jupiter, and then run their simulations for the age of the Solar System to fit the current main belt SFD. Their models are also subject to additional constraints including the number of known asteroid families from large ($D > 100$ km) parent bodies, asteroid (4) Vesta’s single large impact crater, and the lunar and terrestrial impactor flux.

The capabilities of modern asteroid surveys now allow the serendipitous detection of these disruptions. Surveys such as Pan-STARRS (*e.g.* Kaiser *et al.* 2002; Hodapp *et al.* 2004) and the Catalina Sky Survey (CSS; *e.g.* Larson *et al.* 1998; Larson 2007) have

¹The conversion of H to diameter depends on an assumed geometric albedo. Pravec *et al.* (2012) measured geometric albedos p_V to be ~ 0.057 for C/G/B/F/P/D type asteroids and ~ 0.197 for S/A/L types. We have assumed an average geometric albedo of $p_V = 0.11$ so that $H = 23$ corresponds to 100 m diameter and $H = 18$ corresponds to 1 km diameter.

improved in capability to routinely detect active objects in the main belt. When a survey is well-characterized (Jedicke *et al.* 2002) it is possible to measure or set limits on disruption rates that constrain the behavior of large-scale main belt collisional models (*e.g.* Walsh *et al.* 2009; Bottke *et al.* 2005).

It remains difficult to observationally identify the cause of activity in main belt objects. All of the aforementioned mass loss mechanisms produce clouds of dust or ice grains causing a comet-like appearance and often a dramatic increase in brightness. The range of behaviors includes; asteroid P/2010 A2, whose tail structure suggests either an asteroid impact (Snodgrass *et al.* 2010) or YORP-induced rotational breakup (Agarwal *et al.* 2013); the long dust tails of main belt comets like 133P/Elst-Pizarro (Hsieh 2009), compatible with embedded volatiles escaping the parent body after perihelion; and P/2012 F5, activated due to an impact (Stevenson *et al.* 2012). At the extreme end is the 2007 outburst of comet 17P/Holmes, whose apparent brightness increased by 15 magnitudes (from +17 to +2) in 42 hours (Stevenson and Jewitt 2012). The cause of the outburst is unknown but a similar outburst observed during its discovery apparition in 1892 implies an origin related to its inherent nuclear structure and perihelion passage. We include comet 17P/Holmes in our examples even though it is not an asteroid because it illustrates that extreme changes in flux are possible ($\Delta m \sim 20$) and how a bright outburst might appear at main belt distances. Two new members were added to the active main-belt asteroid lineup as of October 2013: P/2013 P5 and P/2013 R3, whose morphologies are suggestive of disruption events (Jewitt *et al.* 2013, 2014).

Despite the increasing numbers of known active main belt objects there has been no verified identification of a collisional catastrophic disruption. We use data from the Pan-STARRS1 all-sky survey and a simple model for a disruption to set an upper limit on the collisional catastrophic disruption rate of main belt asteroids.

2. Method

2.1. Disruption model

Our simple model (fig. 1) for a catastrophic disruption makes no attempt to incorporate the dynamics and interactions of the post-disruption fragments. We simply assume that at time $t = 0$ a parent body of diameter D is catastrophically disrupted into a spherical, homogeneous cloud of particles of diameter d that expands at speed v . Our photometric aperture with diameter a when projected to the location of the disruption views a ‘cylindrical plug’ through the spherical cloud, and our model approximates the reflected light contributed by particles inside the volume of the plug. The change in apparent magnitude as a function of time since the catastrophic disruption can be approximated with:

$$\Delta m(t) = \begin{cases} -2.5 \log_{10} \left[\frac{4v^2}{D^2} t^2 \right] & 0 < t < t_{thick} \\ -2.5 \log_{10} \left[\frac{D}{d} \right] & t_{thick} < t \leq t_{aperture} \\ -2.5 \log_{10} \left[\frac{D_0}{d} \left[1 - \frac{(t^2 v^2 - r_a^2)^{3/2}}{t^3 v^3} \right] \right] & t > t_{aperture} \end{cases} \quad (1)$$

where t_{thick} is the time span during which the dust cloud remains optically thick and $t_{aperture}$ is the time during which the dust cloud is smaller than the projected photometric aperture, r_a is the radius of the projected measurement aperture at the site of the disruption, and $R(t)$ is the radius of the dust cloud as a function of time. The appendix (§4) shows the derivation of this approximation for the magnitude behavior of a catastrophic disruption.

We illustrate our model using a hypothetical impact-generated catastrophic disruption of a 100 m diameter parent body; Bottke *et al.* (2005) predicted that a main belt object of this size is catastrophically disrupted once/year and because we expect that Pan-STARRS1 could detect this type of disruption. The simplification that the entire parent body is transformed into particles of a single diameter is justified by the $n(d) \sim d^{-3.5}$ SFD power-law approximation by Jewitt (2009) describing the differential number of collisional

fragments as a function of diameter. The differential reflected surface area dA contributed by particles of diameter D to $D + dD$ goes as

$$dA = \frac{\pi}{4} D^2 D^{-3.5} dD \quad (2)$$

and the cumulative normalized contribution $A_{cumul}(D)$ in reflected surface area for particles smaller than size d is then

$$A_{cumul}(D) = K \left[D_{min}^{-0.5} - D^{-0.5} \right] \quad (3)$$

where K is a normalization constant that produces 1 for large D , so that $A_{cumul}(D)$ represents the fraction of total reflecting area contributed by particles of diameter D or smaller. (eqs. 2 and 3 use capital D for readability; hereafter, we use D to refer to parent body diameter and d to particle diameter). We assume a minimum particle size of $1 \mu\text{m}$; below this size, particles are rapidly swept away by solar radiation pressure and are inefficient scatterers at the nominal $0.6 \mu\text{m}$ bandpass of our measuring system (Fink and Rubin 2012). Under this scenario, a 100 m diameter parent body that suffers a barely-catastrophic disruption leaving a single 80 m diameter remnant, $\sim 90\%$ of the fragments' reflected light derives from particles $< 100 \mu\text{m}$ diameter and $\sim 68\%$ from those $< 10 \mu\text{m}$. The projectile asteroid's mass can be ignored relative to the parent body because it will typically have about 1/10 the diameter of the parent body but only 1/1000 of the total mass in the collision (Davis *et al.* 1989). Thus, without introducing much error, we can set an upper bound on the reflected light (and maximize the detection efficiency) by assuming 100% conversion of the parent body into $d = 1 \mu\text{m}$ diameter particles. For our hypothetical 100 m body, this results in a brightness increase of +20 magnitudes. While 100% conversion represents an upper limit, if as little as 20% of the parent body is converted to $1 \mu\text{m}$ particles, the resulting dust cloud would still produce a brightness increase of over 18 magnitudes.

We assume a fixed photometric measurement aperture of $3.0''$ to mimic the detection of a catastrophic disruption by a survey telescope employing automatic identification of point sources (like Pan-STARRS1). This aperture corresponds to a spatial diameter of $a \sim 3,000$ km at the disruption assuming a typical main belt opposition distance of 1.5 AU from Earth.

The expanding dust cloud’s photometric behavior in the aperture for $t > t_{aperture}$ was simply modeled with a fixed magnitude decay rate (τ) in the range from 0.001 to 10 mag d⁻¹. This range incorporates essentially the entire range of decay rates predicted by our simplistic catastrophic disruption model (eq. 1) when we assume a representative dust expansion rate of $v = 1$ m s⁻¹. This rate, in turn, is roughly the geometric mean of the range of ejecta speeds (~ 0.06 m s⁻¹ to ~ 100 m s⁻¹) required to model dust ejected from the ~ 100 m diameter asteroid P/2010 A2 estimated by (Bodewits *et al.* 2011) in their comparison of ejecta from a cratering event in asteroid (596) Scheila in late 2010. Thus, our model implicitly incorporates a range of ejecta speeds and any size-dependence on the progenitor by examining a wide range of magnitude decay rates.

Summarizing our representative case, prior to collision the to-be disrupted 100 m diameter object is too faint to be detected by the system. Immediately following the collision the cross-sectional area of dust-dominated fragments begins increasing rapidly such that the disruption reflects enough light to become visible but remains morphologically indistinguishable from a stellar point source. The expanding dust cloud of $1 \mu\text{m}$ diameter dust particles remains optically thick for ~ 6 d following disruption as it expands to a radius of $\sim 1,000$ km and produces a $\sim 10^8$ increase in flux ($\Delta m = +20$ from eq. 1). There is no further change in the aperture flux until the dust cloud extends beyond the projected measurement aperture. The flux decreases as the dust optically thins and as the cloud expands such that a smaller portion of its volume occupies the measurement aperture. The

disruption model incorporates three phases: 1) an immediate ramp-up in brightness during which the disruption becomes detectable due to rapid expansion of the optically thick dust cloud; 2) a period of nearly-constant brightness during which the dust cloud remains optically thick but is expanding beyond the measurement aperture, or has become optically thin but remains completely within the measurement aperture; and 3) a decay period when the disruption is thinning optically and continuing its expansion well beyond the aperture. Fig. 2 illustrates the change in brightness over time for our representative disruption using various dust expansion velocities.

Motivated by this simple model and its analytical realization in eq. 1, and understanding its limited fidelity, we further simplify our model of the catastrophic disruption as an instantaneous increase in brightness (decrease in magnitude, Δm) followed by a linear decrease in brightness (increase in magnitude) at a rate τ . The ramp-up time in brightness due to disruption and the time spent in the ‘plateau’ are short enough relative to the decay time and the survey observing cadence that they can be omitted from the disruption model. Furthermore, the magnitude decay rate in our analytical model changes by only a factor of 10 from 20 to 200 days without even accounting for gravitational reaccumulation of the fragments (not relevant for 100 m bodies (Jewitt *et al.* 2014)), solar radiation pressure, or any other physics, so that our constant-decay model can span the predicted decay rates. Thus, the apparent magnitude at time t after a disruption that occurs at time t_{CD} is then

$$m_{CD}(t) = m_0 - \Delta m_{CD} + \tau (t - t_{CD}) \quad (4)$$

where m_0 is the parent body’s undisrupted apparent magnitude. We will calculate the confidence limit on the catastrophic disruption rate, *i.e.* the largest asteroid that can be disrupting at the rate of one per year, for $0 < \Delta m < 20$ and decay rates τ in the range from 10^{-3} to 10 mag d^{-1} as suggested by our analytical model and the known set of active asteroids. Fig. 3 shows the *change* in magnitude decay over time of our representative

disruption. For a range of dust dispersion velocities from 0.5 to 5.0 m s^{-1} we expect to see a magnitude decay rate between 0.01 and 0.1 mag d^{-1} , except for case involving a rapidly expanding dust cloud, *e.g.* 5 m s^{-1} . In this case the decay in brightness can be quite rapid, several tenths of a magnitude per day, once the optically thick phase is over or the cloud has expanded beyond the projected measurement aperture.

2.2. Catastrophic disruption rate limit

The expected number of *new* detected catastrophic disruptions in a survey time range $[t_{min}, t_{max}]$ with apparent magnitude V brighter than some arbitrary brightness limit V_{CD} and a magnitude profile described by Δm and τ is

$$N_{CD}(\Delta m, \tau; V_{CD}) = \int_{t_{min}}^{t_{max}} dt \int d\vec{x} \int dH \epsilon(\vec{x}, H, t; \Delta m, \tau) f(\vec{x}, H) n(\vec{x}, H) h[(V_{CD} - V(\vec{x}, H, t; \Delta m, \tau)] \quad (5)$$

where \vec{x} represents the six orbital elements, $(a, e, i, \Omega, \omega, M)$, the semi-major axis, eccentricity, inclination, longitude of the ascending node, argument of perihelion, and mean anomaly respectively; H represents the pre-disruption absolute magnitude; ϵ is the system efficiency at detecting the catastrophic disruption; $f(\vec{x}, H)$ is the fraction of objects disrupted per unit time; $n(\vec{x}, H)$ is the number density of objects; and $h(z)$ represents the Heaviside function with $h = 0$ for $z < 0$ and $h = 1$ for $z \geq 0$ that enforces the apparent magnitude of the catastrophic disruption to be $\leq V_{CD}$. We will select a V_{CD} such that there are no known catastrophic disruptions brighter than this threshold so that we can compute an upper limit to the catastrophic disruption rate.

To compute this limit, and for comparison with theoretical modeling, the evaluation of eq. 5 requires us to combine the main belt number density and disruption fraction into

an orbit-independent catastrophic disruption frequency: $\phi(H) \approx f(\vec{x}, H) n(\vec{x}, H)$ with the form $\phi(H) = 10^{\beta(H-H_0)}$. *i.e.* we assume that the main belt orbital element distribution is H -independent. The functional form is motivated by the power-law relationship for the expected frequency of disruption events for main belt asteroids as determined by the CoDDEM simulations by Bottke *et al.* (2005) over the 4.6 Gyr lifetime of the Solar System.

We converted¹ the CoDDEM simulations’ (Bottke *et al.* 2005) diameter-dependent disruption rate prediction to absolute magnitude (fig. 4), fit it to a power-law of the form $f(H) = 10^{\beta(H-H_0)}$, and found $H_{0,Bottke} = 23.26 \pm 0.02$ and $\beta = 0.573 \pm 0.002$. We adopt the power law slope β into our formulation of the catastrophic disruption rate limit, described below, and are primarily interested in observationally determining H_0^{CL} , the smallest absolute magnitude (largest diameter) at which one disruption is occurring per year. The uncertainties on $H_{0,Bottke}$ and β were obtained by computing the root-mean-square residuals of linear fits to the data in fig. 4 using 2 mag-wide sliding windows from $9 < H < 29$ at 1-mag intervals.

The catastrophic disruption detection efficiency calculation is discussed in detail below (§2.5) where we will subsume the efficiency with the requirement that the catastrophic disruption have apparent magnitude $V < V_{CD}$ into a single orbit element and time-averaged function:

$$\bar{\epsilon}(H; \Delta m, \tau, V_{CD}) \approx \epsilon(\vec{x}, H, t; \Delta m, \tau) h[(V_{CD} - V(\vec{x}, H, t; \Delta m, \tau)] \quad (6)$$

We assume disruptions occur independently at a steady rate and are Poisson-distributed over time. If we select a brightness threshold V_{CD} for which there is a single candidate disruption at this brightness and none brighter in our dataset, we can compute a 90% confidence limit (C.L.) on H_0 , the largest diameter asteroid at which one catastrophic disruption occurs per year by integrating over H multiplied by our system detection efficiency and the number of disruptions predicted by the Bottke *et al.* (2005) power law,

then solving for H_0 :

$$H_0^{CL}(\Delta m, \tau, V_{CD}) = \frac{1}{\beta} \log_{10} \left[\frac{\Delta t}{3.9} \int dH \bar{\epsilon}(H; \Delta m, \tau, V_{CD}) 10^{\beta H} \right] \quad (7)$$

where $\Delta t = t_{max} - t_{min}$ is the survey’s time duration.

2.3. The Pan-STARRS1 survey

The Pan-STARRS1 telescope (*e.g.* Kaiser *et al.* 2002; Kaiser 2004; Hodapp *et al.* 2004) began operations in late 2008 as a composite survey to satisfy the various science goals of the Pan-STARRS1 Science Consortium. At survey inception $\sim 85\%$ of the total survey was executed using cadences suitable for asteroid detection; that is, the telescope obtained at least two exposures at the same footprint separated by 10 to 30 minutes. The original asteroid discovery program of producing orbits from pairs of observations over multiple nights (Kubica *et al.* 2007) was quickly found to be ineffective due to the larger-than-expected impact of detector gaps and false detections. The Pan-STARRS1 asteroid survey was reworked in 2010 into a single-night discovery mode using ‘quads’ (4 exposures per footprint separated by ~ 15 minutes) for its dedicated Solar System time and to opportunistically utilize the other survey modes when possible.

Beginning in early 2010 5% of the survey time was dedicated to detection of Solar System objects, in particular near earth objects (NEOs), and this fraction increased to 11% as of November 2012. The Solar System survey uses the wide-band w_{P1} filter and reaches $V \sim 21.5$ (Denneau *et al.* 2013). The remaining survey time useful for asteroid detection consists of 1) the all-sky, multiple filter, 3π survey, that acquires pairs of exposures in each of Pan-STARRS1’s g, r, i, z, y filters (from here on called $g_{P1}, r_{P1}, i_{P1}, z_{P1}$, and y_{P1}) and 2) the Medium Deep Survey, a ‘deep drilling’ survey that obtains 8×240 -second sequences at ten different fixed footprints throughout the year. The 3π survey has a single-epoch point

source sensitivity of $V \sim 20.5$ in the g filter and $V \sim 21$ using r and i .

Successive Pan-STARRS1 images at the same footprint are automatically reduced by the Pan-STARRS1 Image Processing Pipeline (IPP; Magnier 2006) and then subtracted pairwise to identify transient detections. IPP delivers catalogs of transient detections to the Moving Object Processing System (MOPS; Denneau *et al.* 2013). MOPS assembles ‘tracklets’, associations of transient detections across multiple exposures at the same footprint from the same night that *may* represent a real asteroid, that typically contain 3 or 4 detections from a ‘quad’. MOPS also creates tracklets from the Medium Deep survey’s 8-exposure sequences and from pairs of 3π exposures. IPP achieves better than 0.05 mag photometric uncertainty for bright asteroids detected in the subtracted images and $\sim 0.15''$ astrometric uncertainty (Milani *et al.* 2012) for all asteroids over the entire sky. Pan-STARRS1 has delivered more than 7 million detections to the IAU Minor Planet Center (MPC) as of February 2014.

The Pan-STARRS1 3π observing cadence is designed to obtain tracklets at six epochs in each lunation with the g_{P1} , r_{P1} , and i_{P1} filters. In theory, this cadence should have enabled Pan-STARRS1 to perform enough self-followup of each detected object to allow an orbit determination. In practice, the combined effects of weather losses and detector gaps conspired to rarely allow an orbit calculation. Thus, nearly all Pan-STARRS1 ‘interesting’ asteroids and comets are confirmed with other observational facilities.

2.4. Disruption candidate search

Our search for main belt catastrophic disruption candidates relies on the determination by the MPC that a Pan-STARRS1 asteroid tracklet cannot be linked with a known object. We argue that such an unlinked tracklet observed in opposition with main-belt motion

represents a catastrophic disruption candidate if it is brighter than the limit to which the main belt population is believed to be complete.

Unlinked tracklets for all observatories are published regularly by the MPC in its ‘one-night stand’ (ONS) file. The Pan-STARRS1 contributions to the ONS file (fig. 5) are usually a) NEOs that were not followed up and are now ‘lost’; b) faint main-belt asteroids seen too few times to produce an orbit; or c) false tracklets due to image artifacts or mis-linkages that were submitted automatically by MOPS.

A Pan-STARRS1 tracklet composed of *bright* detections in the ONS with main belt-like rates of motion must therefore be a main belt asteroid that has escaped detection until now, or an NEO ‘hiding in plain sight’ (both exceedingly unlikely for bright objects), or a small main belt asteroid activated into detectability due to a disruption event. The brightest real, unlinked Pan-STARRS1 tracklet satisfying these conditions over the period 2011-02-21 through 2012-05-19, submitted with the identifier P1010ae, has apparent magnitude $V = 18.5$ (fig. 5 and table 1). The detections in the P1010ae tracklet have a positional great-circle residual of $0.04''$ and photometric variation of 0.07 mag, consistent with expectations for a main belt object. The detections show no sign of ‘activity’ as they are morphologically consistent with the point-spread functions (PSF) of nearby flux-matched stars.

Main belt asteroids with apparent magnitude $V < 16.5$ are nearly certain (fig. 6) to have absolute magnitudes less than the completeness limit of $H = 15$ reported by Gladman *et al.* (2009). We suggest that the main belt is complete to a smaller size limit corresponding to $H \sim 17.5$ because our disruption candidate, P1010ae with $V = 18.5$, is the brightest unlinked (unknown) Pan-STARRS1 tracklet in the MPC ONS file. Figure 6 shows the probability that a main belt asteroid detected near opposition has $H < H_{complete}$ as a function of its apparent magnitude for $H_{complete} = 15, 16$ and 17 . We see that an

asteroid near opposition with $V = 18.5$ is virtually certain to be known if the main belt is complete to $H_{complete} = 17.5$. We base this statement on the fact that millions of asteroids have been observed in opposition in Pan-STARRS1, and if the main belt were not complete to $H_{complete} = 17.5$, there should be many unlinked ONS tracklets with apparent magnitude brighter than $V = 18.5$ when there are none (there are only a handful brighter than $V = 19$). But even if P1010ae is in fact only a main belt asteroid, and not the remnant of a catastrophic disruption, our computed catastrophic disruption rate limit based on this brightness threshold remains valid because there are still no detected catastrophic disruptions *brighter* than $V = 18.5$ and we have simply overestimated the upper limit on the rate.

We use the MPC **digest2** score² (Jedicke 1996) to determine whether a single-night tracklet is likely to be a main belt asteroid. **digest2** generates a set of virtual orbits that are statistically compatible with the input tracklet (*e.g.* Virtanen *et al.* (2001); Muinonen *et al.* (2006)) to compute a pseudo-probability that a tracklet belongs to a particular asteroid population. It is used by asteroid surveys to select tracklets for immediate followup (typically NEOs) that have not been associated with known objects. In this study we selected ONS tracklets that have **digest2** scores of > 25 for at least one of the MB1 (inner), MB2 (middle) or MB3 (outer) main belt classes.³

To summarize: we use the MPC ONS database and the **digest2** computation to select an unknown asteroid with main belt motion with a brightness that suggests the asteroid

²**digest2** was developed by S. Keys, C. Hergenrother, R. McNaught, and D. Asher, and is available at <https://code.google.com/p/digest2>.

³In **digest2**, MB1 is defined generally as $2.1 < a < 2.5$ and $q > 1.67$, MB2 as $2.5 < a < 2.8$, and MB3 as $2.8 < a < 3.25$, where a is the orbital semi-major axis and q the perihelion distance in astronomical units.

has a size in the complete population. Since it is unknown, we consider it a candidate catastrophic disruption and choose its apparent magnitude as V_{CD} for eq. 7.

Our calculation of the main belt catastrophic disruption rate limit requires that we identify candidate disruptions that occur *in* our observation window. A possible source of confusion is disruption(s) that occur prior to the observing window but remain visible. The ability of the current asteroid surveys to repeatedly image the main belt near opposition in single or adjacent lunations suggests that a bright, slowly-decaying disruption would be observed on multiple nights and linked by the MPC into an asteroid orbit; *i.e.* it would not appear in the ONS and is unlikely to be one of our candidate disruptions. Conceptually this situation could lead to slow-decaying disruptions ‘hiding’ undetected in Pan-STARRS1 data, leading to an erroneous computation of the limit. However, recent discoveries of faint ($m > 20$) active asteroids identified automatically by current all-sky surveys suggest that a slow-decaying disruption brighter than our candidate object ($m < 18.4$) would eventually have been detected by virtue of its comet-like appearance by at least one of the surveys and would therefore be confirmed as an actual disruption having a disruption date outside our survey window. That no such event was observed leaves us confident that our single ONS candidate with magnitude $V = 18.5$ represents the brightest possible catastrophic disruption in our observation window. Since our simple model allows for a brightness increase of up to 20 magnitudes post-disruption, an additional consideration is a slow-decaying disruption that actually saturates the detectors of current surveys, rendering them ‘undetected’ by automatic source-finding software. We argue that an event such as this occurring in the main belt would have an obvious cometary signature and would similarly result in a confirmed disruption.

Alternatively, bright, rapidly-decaying disruptions, *e.g.* $> 0.1 \text{ mag d}^{-1}$, are unlikely to be observed again by current all-sky surveys because they fall below the systems’s

detection thresholds within weeks. Thus a rapidly-decaying disruption occurring prior to but detectable within the observation window would have to occur close enough in time to essentially be considered ‘in’ the window. Fig. 7 illustrates this reasoning schematically. Note that we are not strongly concerned with whether our candidate ONS tracklet is truly a disruption – it may simply be an unknown (at time of observation) main belt asteroid. While our analysis of main belt completeness suggests that the number of unknown main belt asteroids that can have brightness $V = 18.5$ in opposition is exceedingly small, this would not affect the validity of our computed catastrophic disruption rate limit, as we are still stating that there are no catastrophic disruptions *brighter* than our candidate.

2.5. Pan-STARRS1 detection efficiency for catastrophic disruptions in the main belt

The Pan-STARRS1 MOPS software allows us to measure the system’s efficiency (used in eq. 7) by injecting synthetic detections into the processing stream to determine how many objects would be detected. Faint objects can be missed simply because they are not brighter than the system’s limiting magnitude but even bright objects can go undetected if they saturate the detector, fall in a gap between the detectors, or are embedded in a bright star’s PSF.

For this study, we were not interested in the detection of asteroids *per se* but the aftermath of the catastrophic disruption of an asteroid according to our model. Intuitively we expect that disruptions with larger changes in brightness (Δm) and longer decay times (τ) should be easier to detect, as large changes in magnitude mean that disrupted small asteroids will become bright enough to be detected, and long decay times give the survey a longer window in which the disruption is detectable. At the same time, the very brightest disruptions will saturate the system’s detector, resulting in a window of detectability where

the disruption is brighter than the system sensitivity limit yet below the saturation limit.

We employed MOPS using Pan-STARRS1 telescope pointings over the 453-day interval from $t_{min} = 2011-02-21$ through $t_{max} = 2012-05-19$ and a realistic distribution of 1.5M main belt objects from a synthetic Solar System model (S3M; Grav *et al.* 2011). We exploited our assumption of the separability of the main belt objects’s orbit distribution from H and assigned all the 1.5M main belt objects (candidate parent bodies) an absolute magnitude of $H_{ref} = 18$ (the actual value does not matter). The objects were propagated to the times of observation of all the Pan-STARRS1 exposures and those objects that were located in any field of view (FOV) were stored in a database as ‘in-field detections’. *i.e.* we stored them in the database regardless of their apparent magnitude at the time they were in the field. Each object in that database has entries that include its time of observation, topocentric position, apparent magnitude V_{ref} , and signal-to-noise ratio. Approximately 1M of the 1.5M synthetic asteroids appear in the $\sim 60,000$ survey fields, an average of ~ 100 per exposure. The advantage of this technique is that we can assign any other absolute magnitude $H' = H_{ref} + \Delta H$ to an object and its apparent magnitude in any field i will simply be $V'_i = V_{i,ref} + \Delta H$.

We randomly selected $N = 1,000$ of the objects to undergo a catastrophic disruption for each Δm , τ , and H' combination in a grid of 0.5 mag steps for $0.5 \text{ mag} < \Delta m < 20 \text{ mag}$, 0.08 dex for $0.001 \text{ mag d}^{-1} < \tau < 10 \text{ mag d}^{-1}$, and 0.5 mag steps for $14 \text{ mag} < H' < 30 \text{ mag}$. The catastrophic disruptions occurred at random times distributed uniformly over the simulation interval and their subsequent apparent magnitude followed eq. 4. We then applied the filter- and survey-dependent Pan-STARRS1 tracklet identification efficiency (Denneau *et al.* 2013) to each of the observed synthetic catastrophic disruptions. The Pan-STARRS1 fill-factor of ~ 0.75 results in a tracklet identification efficiency of ~ 0.7 for the creation of 3- or 4-detection tracklets from the four exposures obtained in

the w_{P1} filter Solar System survey. The g_{P1} , r_{P1} and i_{P1} observations have a tracklet identification efficiency of ~ 0.5 because they are acquired using pairs of exposures to create 2-detection tracklets. We set the detector’s saturation limit at the brightest V -band magnitude reported for an asteroid by Pan-STARRS1, (92) Undina with apparent magnitude $i_{P1} = 13.3$ or $V = 13.7$. The catastrophic disruption detection efficiency is then $\epsilon(\Delta m, \tau, H, V_{CD}) = n(\Delta m, \tau, H)/N(\Delta m, \tau, H)$, where n is the number of detected synthetic catastrophic disruptions in a Pan-STARRS1 field brighter than our candidate disruption P1010ae ($V = 18.5$) but not saturating the detector and N is the number of generated disruptions (1,000).

The calculated Pan-STARRS1 detection efficiency (fig. 8) for catastrophic disruptions of main belt objects agrees with our expectations that long-lived and brighter events are easier to detect (brighter by virtue of parent body size or increase in brightness). The maximum detection efficiency of about 50% in each H slice always corresponds to the slowest magnitude decay rate of 0.001 mag d^{-1} . At the slowest decay rates the disruptions’s aftermath decreases in brightness by only about 0.5 mag in the course of the 453 day duration of the survey data — so, if it is detectable, it is detectable the entire time. The survey duration corresponds to the synodic period of main belt asteroids with semi-major axes of $\gtrsim 3 \text{ AU}$ so that almost every disruption further from Earth at opposition than about 2 AU will be covered if it is above the system’s limiting magnitude. On the contrary, about 60% of main belt objects have synodic periods $\gtrsim 453 \text{ d}$ so that the survey’s completeness for main belt objects is distance-dependent. This factor, combined with the system’s limiting magnitude and saturation limit, the survey coverage, and the camera’s fill-factor conspire to result in a maximum catastrophic disruption detection efficiency of ~ 0.5 . The pattern of the efficiency contours shifts to larger Δm as the absolute magnitude of the parent body increases because smaller objects require larger changes in flux so that they are bright enough to be detected.

2.6. Catastrophic disruption rate limits

Our 90% confidence limit contours on H_0 (fig. 9) represent the largest object at a given $(\Delta m, \tau)$ that can be disrupted in the main belt at the rate of one per year and still be consistent with the Pan-STARRS1 data; *i.e.* the actual H_0 value must be greater than the contour value at $(\Delta m, \tau)$. The contours are generated by computing H_0^{CL} from eq. 7 at equally-spaced $(\Delta m, \tau)$ grid points. We draw lines of constant H_0 that indicate what brightness behavior, described by $(\Delta m, \tau)$, is allowed for a given constant H_0 contour to satisfy the computed limit H_0^{CL} at the $(\Delta m, \tau)$ location. Because we have computed a limit, a given H_0 contour defines a boundary of behavior, *i.e.* ‘allowed’ values for H_0 for a given $(\Delta m, \tau)$ lie along the boundary or above and to the left, where objects are smaller.

Our computed limit space spans more than 20 absolute magnitudes in our $(\Delta m, \tau)$ parameter space from $8 < H_0^{CL} < 30$. We see that slowly-decaying disruptions with large magnitude changes with $\Delta m = 15$ and $\tau = 0.001 \text{ mag d}^{-1}$) yield $H_0^{CL} \sim 27$, or about 15 m in diameter. Even though in this case the parent body is smaller than a house, the disruption of such a body is bright and long-lived enough to be easily detectable by Pan-STARRS1. At the opposite end, fast-decaying disruptions with small brightness changes (*e.g.* $\Delta m = 0.5$, $\tau = 10 \text{ mag d}^{-1}$) would be detected so rarely by Pan-STARRS1 that our method can only constrain H_0 to be > 10 (about 40 km diameter). The computed limit space in itself does not suggest a particular H_0^{CL} ; it simply describes a relationship between H_0 and $(\Delta m, \tau)$ and we must employ additional based on our simple model and other observational data to narrow down a small region in this space from which we can select H_0^{CL} .

3. Discussion

Table 2 summarizes the relevant properties of the recently discovered active (mass-losing) main belt objects and one near-catastrophic cometary disruption (Reach *et al.* 2010) including our estimates of Δm and τ based on published results. We include those that may be activated by impacts (P/2010 A2, (596) Scheila and P/2012 F5 (Gibbs)), rotational breakup (P/2010 A2 again, P/2013 P5 and P/2013 R3) and several others whose activity is probably produced by other, unknown mechanisms.

Asteroid P/2010 A2 appears twice in fig. 9 because it was first attributed to a impact-generated disruption by Jewitt *et al.* (2010) who estimated $\Delta m = +15_{-0}^{+4}$ assuming a 2 m diameter projectile, but later analysis of precovery observations by (Jewitt *et al.* 2011) and detailed dust-modeling work by Agarwal *et al.* (2013) suggested instead a rotational breakup with $2.3 < \Delta m < 5.5$. Both scenarios allow us to estimate the decay rates assuming a disruption in early 2009 Jewitt *et al.* (2010); $\tau_{collision}$ can be in the range from about 0.055 mag d^{-1} to 0.070 mag d^{-1} and $\tau_{rotation}$ from about 0.008 mag d^{-1} to 0.020 mag d^{-1} to achieve the apparent nuclear magnitude measured in HST observations 270 days later Agarwal *et al.* (2013).

Asteroid (596) Scheila ($\sim 113 \text{ km diameter}^4$) was observed $\sim 11 \text{ d}$ after the impact of a decameter-scale projectile (Ishiguro *et al.* 2011; Bodewits *et al.* 2011) from which we derive $\Delta m = 1.0 \pm 0.1$ and $\tau = 0.087 \pm 0.007 \text{ mag d}^{-1}$. There are no reported nuclear observations of asteroid P/2012 F5 (Gibbs) near the start of activity but we calculate $\Delta m = 2.1 \pm 0.1 \text{ mag}$ based on its pre-impact absolute magnitude of 17.22 ± 0.21 from precovery observations (Novakovic *et al.* 2014) and the post-impact observations of Stevenson *et al.* (2012).

Recent discoveries P/2013 P5 and P/2013 R3 add to an already diverse assortment of

⁴ <http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=596>

active main belt asteroids. Upon discovery in August 2013 the dust surrounding P/2013 P5 exhibited rapidly-changing episodic ‘pinwheel’ behavior. (Jewitt *et al.* 2013) conclude that this body has been spun up by radiation torques to the edge of stability. This effects of episodic, overlapping, mass loss over five months defy simple parameterization using a single brightness increase and decay rate.

P/2013 R3 was discovered in late 2013 already spit into at least 10 comet-like fragments, the largest with an effective diameter $\lesssim 400$ m (Jewitt *et al.* 2014). Analysis of the fragments and surrounding dust suggest a disruption event between February and September 2013. Jewitt *et al.* (2014) measured brightness decreases of individual fragments ranging from 0.005 to 0.64 mag d⁻¹. Averaging these values and extrapolating to the midpoint of estimated disruption dates provides a crude brightness increase of +4 magnitudes at the time of disruption.

The uncertainties on our derived Δm and τ values for individual objects are based purely on the reported uncertainties in the source observations. The actual uncertainty must be considerably larger and is certainly dominated by our incomplete understanding of the nature of the activity. All but one of the derived τ values (table 2) for these objects lies in the range from $\tau = 0.01$ mag d⁻¹ to $\tau = 0.1$ mag d⁻¹ predicted analytically from our disruption model. P/2012 F5 (Gibbs) with $\tau \sim 0.002$ mag d⁻¹ is anomalously low, perhaps because it was initially activated by a cratering event leading to sublimation activity of the newly exposed material.

It is more difficult to constrain Δm because none of the aforementioned known events is thought to represent an collisional catastrophic disruption. Our simple model does not incorporate specific collisional features, so one can argue that rotationally disrupted P/2013 R3 represents the best available model for any catastrophic disruption even with its modest brightness increase of +4 magnitudes. Conversely, for a collisional catastrophic

disruption we expect much larger amounts of dust to be released than from rotational disruption and therefore a greater increase in magnitude than seen for P/2013 R3. Even if 10% of a 100 m parent body is converted to $1\text{ }\mu\text{m}$ dust, we would see a brightness increase of +17.5 magnitudes; the initial collisional analysis of P/2010 A2 by Jewitt *et al.* (2010) corroborates this. It is hard to devise a geometric scenario in an impact event that occludes enough $1\text{ }\mu\text{m}$ dust to prevent brightness increases in +15 – 20 magnitude regime. Thus the aforementioned events provide lower bounds for Δm , but are not thought to represent the brightness behavior of an collisional catastrophic disruption. The event with a brightness increase most similar to the $\Delta m = +20$ predicted by our simple model is the outburst of comet 17P/Holmes with $\Delta m = +17$, but since this object is not asteroidal the comparison is questionable.

With no confirmed collisional catastrophic disruptions and therefore a lack of observational evidence regarding the dust SFD in a catastrophic disruption, it is reasonable to consider that our assumptions about minimum dust particle size of $1\text{ }\mu\text{m}$ and complete conversion of original mass into dust in a collisional catastrophic disruption may simply be erroneous. If a typical disruption produced ‘clumpy’ fragments in which only 10% of the mass is converted to dust $100\text{ }\mu\text{m}$ and larger, the brightness would increase by only +12.5 magnitudes, largely consistent with Bottke *et al.* (2005). We reject this position based on the following considerations: a) small rubble-pile asteroids such as (25143) Itokawa may have interiors dominated by fine dust grains in the micron size regime (Scheeres and Sanchez 2012; Tsuchiyama *et al.* 2011); b) the estimates by Jewitt *et al.* (2010) of a +15 magnitude brightness increase for the sub-catastrophic disruption of P/2010 A2, revised downward after the dust morphology suggested rotational breakup; and c) the apparent scarcity of collisional disruptions among recent disruption events.

If we accept our model’s $\Delta m = +20\text{ mag}$ and adopt a nominal decay rate at

the geometrical mean between 0.01 and 0.1 mag d^{-1} , fig. 9 suggests that the largest bodies undergoing catastrophic disruptions at the rate of one per year have an absolute magnitude no smaller than $H \sim 28.7$, *i.e.* no larger than about 7 m in diameter. Alternatively, we can accept the $H_0 = 23.26$ value that we obtained from a fit to the main belt collisional evolution simulations of Bottke *et al.* (2005). Their results for the resulting main belt SFD are supported by several lines of evidence that they used to constrain their model (see §1). With $H_0 = 23.26$ and the restricted apparent magnitude decay rate range of $0.01 \text{ mag d}^{-1} \lesssim \tau \lesssim 0.1 \text{ mag d}^{-1}$, our results (fig. 9) suggest that $+11.0 \text{ mag} \lesssim \Delta m \lesssim +12.4 \text{ mag}$ — 2 to 4 orders of magnitude smaller in flux than the $+15 \text{ mag}$ to $+20 \text{ mag}$ suggested by our simple disruption model and impact-scenario modeling of P/2010 A2. The naive interpretation of the discrepancy between our H_0^{CL} and the Bottke *et al.* (2005) prediction is simply that the main belt catastrophic disruption rate (collision or otherwise) is actually much lower than they predict. However, while no *impact-generated* catastrophic disruption has yet been observed in the main belt, ongoing all-sky surveys have detected several objects undergoing rotational disruption: P/2010 A2, P/2013 P5 and P/2013 R3. The prevalence of disruption due to rotation with none due to collision suggests that rotational disruption may be the dominant cause of disruption of small asteroids (*e.g.* 100 m diameter and smaller), or that rotational disruptions may occur on longer timescales than collisional disruptions, resulting in an observational bias. While our detection efficiency simulations account for slowly-decaying disruptions, the episodic behavior of P/2013 P5 exposes limitations in our simplistic modeling.

Indeed, the Bottke *et al.* (2005) collisional model did not consider the possibility of rotational-distribution, and attributed the entire collisional cascade evolution to impact-generated catastrophic disruptions, cratering and spallation events. They then fit their collision evolution model and resulting main belt size-frequency distribution to the known population including the smallest objects in the 100 m diameter size range

extrapolated from the NEO population and cratering statistics. By ignoring the rotation-generated catastrophic disruptions their model would over-estimate the size at which one impact-generated disruption occurs per year. But it is these impact-generated catastrophic disruptions that would generate a photometric signature predicted by our simple model. Thus, it may be possible to reconcile the $H_0 = 23.26$ predicted by Bottke *et al.* (2005) with our results by bifurcating the small-body disruption flux into impact-generated and rotation-generated components as suggested by Jacobson *et al.* (2014). If impacts play only a small role in generating main belt catastrophic disruptions it could explain why our study yields a much lower impact-generated catastrophic disruption rate than that predicted by Bottke *et al.* (2005) and why contemporary asteroid surveys regularly identify the aftermath of the rotation-induced disruptions of main belt asteroids. Since the collision cascade evolution models incorporate the impact probabilities between main belt asteroids that are probably not too much in error, the implication is that including the rotation-induced catastrophic disruptions in the evolution models will require a modification of the asteroids’ strength versus size (the Q_D^* specific disruption energy function in their models, *e.g.* (Bottke *et al.* 2005)). These models describe the energies required to disrupt asteroids in both the strength regime (small bodies) and gravitational regime (large bodies), with a minimum unit specific disruption energy Q_D^* occurring between the two regimes near 200 m diameter (Bottke *et al.* 2005). If rotational breakup is much more common than impact disruption at small sizes, the intrinsic strength of these bodies may be weaker than predicted by current theories.

Jacobson *et al.* (2014) suggest that the timescale for YORP-induced rotational acceleration to the point of disruption for a 100 m diameter main belt asteroid with semi-major axis of 2.5 AU is on the order of about 0.5 Myr while Farinella *et al.* (1998) estimate that the impact-generated disruption of the same size object occurs on a timescale of ~ 200 Myr. *i.e.* rotation-induced disruption occurs about $400\times$ more frequently at the

asteroid sizes to which modern surveys are sensitive. Indeed, rotation-induced catastrophic disruptions should dominate the detected population of catastrophic disruption events.

Finally, we can compare the ratio of the number of main belt objects at our $H_0^{CL} \sim 28.7$ (about 7 m diameter) to the number of $H_0 \sim 23.3$ (100 m) asteroids to determine whether our measured deficit in the impact-generated catastrophic disruption rate can be recovered by the much more larger rotational catastrophic disruption rate found by Jacobson *et al.* (2014). The SFD is not well measured in this size range but an accurate value is not important and we simply assume a canonical dependence on the absolute magnitude proportional to $10^{0.5H}$ (Dohnanyi 1969, 1971). In this case the ratio between the $H = 28.7$ and the $H = 23.3$ populations is a factor of about 500 — comparable to the ratio between rotation-induced and impact-generated catastrophic disruptions. In other words, our confidence limit and simplistic model may in fact be consistent with the observations: impact-generated catastrophic disruptions of asteroids in the 100 m diameter range are extremely rare and the data suggests with 90% confidence that the impact-generated catastrophic disruptions have $H_0^{CL} < 28.7$.

Future efforts to improve upon our H_0^{CL} limits should take into account the following considerations:

- Our catastrophic disruption model and its implementation as a simple linear decay in apparent magnitude is certainly too simplistic to represent their actual photometric behavior. Instead of a rapid increase in flux followed by a slow decay, there may be a period of rapid decay during which small particles evacuate the system due to solar radiation pressure, followed by slower decay as the larger particles disperse. This would lead to a shorter period of detectability for small (*e.g.* 100 m diameter) objects and push H_0^{CL} toward larger diameters (smaller H_0^{CL}).
- We have assumed that the central region of a main belt catastrophic disruption

as viewed from Earth will be detectable with the automated Pan-STARRS1 IPP software. This requires that there be a central ‘nuclear condensation’ in the photometric aperture. These assumptions have not been tested, though we know that Pan-STARRS1’s detection efficiency for ‘fuzzy’ objects is not zero because the system has discovered ~ 40 comets based on their almost-but-not-stellar PSFs. A detection system that could automatically detect and characterize extended sources would have a much higher detection efficiency for catastrophic disruptions.

- Main belt collisional evolution models (*e.g.* Bottke *et al.* 2005; O’Brien and Greenberg 2003) are currently only constrained by the measured main belt SFD for asteroids $\gtrsim 1$ km diameter so the models may overestimate the number of objects in the small size regime that contribute to the catastrophic disruption ‘signal’. If there are fewer small main belt asteroids than predicted then the rate of detectable catastrophic disruptions might be less than expected. Willman *et al.* (2010) proposed that there is a deficit in the number of small main belt objects based on space weathering gardening times and (Chapman *et al.* 2002) make the same proposition to explain the unexpectedly low number of craters on asteroid (433) Eros. O’Brien (2009) however argue that this deficit is due to seismic shaking erasing the small craters.
- Our ranges for Δm and τ may not be representative of the behavior of catastrophic disruptions. Fig. 9 shows that there is much more than a factor of 10 difference in the measured magnitude decay rates between outburst events (*e.g.* P/2012 F5 and P/2010 A2), and Δm is not constrained by any observations of impact-generated catastrophic disruptions.
- There may be a parent body size-dependence that is not captured by our catastrophic disruption model. The ~ 113 km diameter⁴ asteroid (596) Scheila is thought to have been struck by a decameter-sized object (Jewitt 2012) that resulted in the

creation of a crater and which caused a sudden ~ 1 mag brightness increase that faded over the course of one month. We calculated its brightness decay rate to be $0.087 \pm 0.015 \text{ mag d}^{-1}$, the fastest in our sample, using an impact date estimated by Ishiguro *et al.* (2011) and nuclear photometric measurements by Bodewits *et al.* (2011). Even though this event was a cratering event it illustrates that the largest surviving fragment after disruption can recapture dust particles that would otherwise contribute to an expanding dust cloud.

- The assumption here and in main belt collisional evolution models of the separability of the main belt objects’s (a, e, i) from their absolute magnitudes H is certainly not correct in detail. For instance, main belt families have different SFDs (*e.g.* Parker *et al.* 2008) from the background population and occupy distinct regions in orbit element phase space (*e.g.* Zappala *et al.* 1990; Milani and Knezevic 1994). Thus, there are certainly locations in the (a, e, i, H) phase space where catastrophic disruptions are more or less likely to occur and this will alter their detectability by asteroid surveys.
- The properties of dust evolution after a catastrophic disruption has not been investigated and our assumption that all the mass is converted into $1 \mu\text{m}$ dust particles is clearly an oversimplification. For instance, Sánchez and Scheeres (2013) have shown that van der Waals forces between regolith grains can lead to a scale dependence in asteroid strength. The same force would lead to ‘clumpiness’ in the dust cloud after a disruption and reduce the cross-sectional area of the dust and the observed Δm .
- The contribution of rotation-induced catastrophic disruptions to small-body physical evolution must be understood (*e.g.* Jacobson *et al.* 2014). Recent events and objects like P/2010 A2, P/2013 P5 and P/2013 R3 may help establish the relative contribution of rotation- and impact-generated catastrophic disruptions.

Looking forward, we can predict the annual number of catastrophic disruptions that will be detected with $V < 18.5$ using ongoing and upcoming asteroid surveys (table 3) assuming that our single Pan-STARRS1 catastrophic disruption candidate is real. Table 3 provides our conservative estimates for the ‘catastrophic disruption survey efficiency’ relative to Pan-STARRS1 based on real or anticipated areal sky coverage, limiting magnitude, cadence, weather losses and observing efficiencies. For the purpose of this estimate we define the useful main belt catastrophic disruption search area as a region 60° wide in ecliptic longitude $\times 30^\circ$ high in ecliptic latitude centered at the opposition point. We note that the search for very bright main belt objects like the immediate aftermath of a catastrophic disruption might actually benefit from surveying *further* from opposition where phase angle effects reduce an event’s apparent brightness so that it does not saturate the detector. The catastrophic disruption survey efficiency increases with the opposition area coverage, limiting magnitude, and per-exposure detection efficiency. The effect of a more rapid cadence is more complicated because it can allow for both detection of faster-decaying events and compensate for area loss on the detector by allowing multiple opportunities to observe an event. Conservatively, we allow that multiple coverage of the opposition region per lunation increases the detection efficiency to 100% and that re-observations across lunations provide a factor of 2 improvement.

The opportunity for discovering and studying more catastrophic disruptions of small main belt asteroids in the next decade is promising (table 3) — if our single Pan-STARRS1 candidate is real. If it is not real the predicted number will drop, but it cannot decrease too much without becoming seriously in conflict with the predictions of the main belt collision models (*e.g.* Bottke *et al.* 2005; O’Brien and Greenberg 2003). The surprising prediction that ATLAS (Tonry 2011) might detect about a dozen catastrophic disruptions per year is due, perhaps paradoxically, to its very bright saturation limit at $V \sim +6$ and its rapid all-sky cadence. Anything on the sky brighter than about $V = 18$ moving with main

belt-like rates of motion must be something unusual because all the asteroids with apparent $V < 18$ are known. Thus, ATLAS may detect catastrophic disruptions of decameter-scale diameter main belt asteroids. Curiously, LSST’s saturation limit of $V = 18$ (Kantor 2013) ensures that it will discover nearly zero disruptions with $V < 18.5$ but it should excel at the discovery of catastrophic disruptions by identifying them with their morphological behavior.

It may be possible to identify the remnants of other catastrophic disruptions via a thorough search of the MPC’s dataset beyond the ONS file. The measured magnitude decay times for P/2010 A2 and other active main belt asteroids suggest that a plausible catastrophic disruption scenario consists of a small (*e.g.* 100 m) diameter asteroid disrupted into visibility, decaying slowly enough that corresponding tracklets are reported to the MPC by multiple surveys, after which the object is designated a ‘new’ main belt asteroid. Observations of such an object would not appear in the MPC’s ONS file as subsequent observations could be associated with the initial orbit of the disrupted asteroid. The signature of a disruption would be its sudden appearance (*i.e.* the object would not be present in precovery images where one would expect to find it if it were a normal asteroid) followed by the secular decay of its measured absolute magnitude and, of course, associated morphological behavior. The discovery of such an object would improve our understanding of brightness decay rates of objects undergoing disruption or further restrict the calculated rate limit if no objects are discovered. Cikota *et al.* (2014) mined the MPC observation catalog to search for low-level activity in the main belt and found four candidate asteroids not previously known to exhibit activity. Their success suggests that a search for sudden turn-on objects may turn up several candidate disruptions.

The slow-decay scenario (*i.e.* small τ) with followup is a class of disruption behavior that would not be detected using our technique that specifically requires the event to appear in the MPC ONS file. These disruptions would be visible for years and be ‘discovered’ as

main belt asteroids and therefore be omitted from that file. Thus, if this scenario is common it would lead us to under-estimate the disruption rate. Such an event can not exist in the Pan-STARRS1 dataset due to the small likelihood of the survey obtaining self-followup of any object in our time window (§2.3). The improving efficacy of contemporary all-sky surveys in identifying unusual photometric and morphological behavior in asteroid detections (*e.g.* (593) Scheila, P/2012 F5 (Gibbs), P/2013 P5 and P/2013 R3) suggests that when such an event occurs in the main belt, the event would be detected and verified as a disruption and could be used in place of our candidate bright ONS tracklet to measure H_0 (this would also require an analysis of the survey’s catastrophic disruption detection efficiency that allows for discovery of this type of catastrophic disruption event).

4. Conclusions

We have set limits on the rate of impact-generated catastrophic disruptions in the main belt using the detection of the brightest unknown object that had main belt-like motion (with $V = 18.5$) during 453 days of sky surveying with Pan-STARRS1. That object must either be a generic but unknown main belt asteroid with $H \sim 16.5$ or an unknown small asteroid undergoing a transient increase in brightness. We can not determine what type of ‘activation’ process might have created the event but, since catastrophic disruptions are the least likely of all of them, assuming that it is a catastrophic disruption provides a conservative upper limit on the disruption rate. Our catastrophic disruption rate limit $H_0^{CL}(\Delta m, \tau)$ is stated in terms of the absolute magnitude H_0 at which one main belt asteroid is catastrophically disrupted per year and is provided as a function of the magnitude increase due to the disruption (Δm) and the magnitude decay rate (τ) during the post-disruption time period as the remnant dust cloud dissipates. Our simplistic model of the photometric behavior of an impact-generated catastrophic disruption suggests that

$\Delta m \sim +20$ and $0.01 \text{ mag d}^{-1} \lesssim \tau \lesssim 0.1 \text{ mag d}^{-1}$ which leads to the conclusion that our 90% confidence limit requires that $H_0^{CL} \gtrsim 28.7$.

Our H_0^{CL} limit is in strong disagreement with the expected value of $H_{0,Bottke} \sim 23.3$ from contemporary main belt collisional evolution models (*e.g.* Bottke *et al.* 2005; O’Brien and Greenberg 2003). Their H_0 value requires $11.0 \text{ mag} \lesssim \Delta m \lesssim 12.4 \text{ mag}$ if they are to occur once per year. Even the uppermost value in this range is much smaller than the $\Delta m = +20$ predicted by our simple dust model for the brightness increase in the aftermath of an impact-generated catastrophic disruption of a 100 m diameter asteroid and from modeling the impact-generated disruption scenarios for asteroid P/2010 A2 (Jewitt *et al.* 2010).

The discrepancy between our measured $H_0^{CL} = 28.7$ modeled using impact-scenario brightness profiles and the expected $H_{0,Bottke} = 23.26$, in combination with the recently observed rotation-induced disruptions of main belt asteroids, suggests that the dominant cause of disruption for small asteroids and is non-collisional, namely YORP spin-up disruption. The discrepancy can be reconciled by allowing spin-up disruptions, which are $400\times$ more common than impact disruptions, to have brightness increases less than those for impact-generated events but with similar decay rates. We find then that overall disruption rate (impact and rotational) is then consistent with the predictions of Bottke *et al.* (2005). We can assume that a rotational breakup of a $D \simeq 100$ m rubble pile asteroid occurs at a spin period of $P \simeq 2.2$ hours (Harris 1996). If this occurs then equatorial material will leave the asteroid at the rotation speed of $\sim 2 - 3 \text{ m s}^{-1}$, similar to that assumed in our collisional disruption model. However it may be that such disruptions occur over long periods, with the asteroid gradually fragmenting via episodic mass-loss as appears to be the case for P/2013 P5. In this case the magnitude increase at any time within the photometric aperture will be far smaller than for an instantaneous disruption.

The steadily improving capability of asteroid surveys such as Pan-STARRS1 and the Catalina Sky Survey are working towards the constant monitoring of main belt asteroids in the night sky. Their ability to detect fainter, smaller asteroids will enable deeper completeness of the main belt SFD, which in turn allows for easier and more frequent detection of anomalous activity. These surveys are already detecting a handful of unusual events per year, and upgrades to the detection capability of both surveys could improve this number by a factor of several by mid-2015, with additional improvement from surveys currently under construction. The detection of an unambiguous catastrophic disruption event is imminent.

The ATLAS survey (Tonry 2011), dedicated to scanning the entire sky nightly to search for ‘death-plunge’ asteroids, will provide additional monitoring of the bright end of the main belt. It will be capable of accurate photometry of sources as bright as $V = 6$, a regime where bright, rapidly-fading disruptions can not be monitored by current surveys because their detectors saturate at much fainter magnitudes.

Active main belt asteroids with unusual morphologies such as P/2010 A2, P/2013 P5, and P/2013 R3 are guiding the way to more sophisticated dust and fragment modeling of disruption scenarios. These models, combined with a future steady stream of disrupted objects and improved survey characterization, will lead to a better understanding of main belt evolution based upon a wealth of observational data complemented by more sophisticated dynamical evolution and catastrophic disruption models.

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Appendix

Assume we have an asteroid of diameter D_0 that disrupts instantaneously into a ‘cloud’ of particles of diameter d that expands linearly in time with speed $2v$. *i.e.* the fastest particles are moving outwards at speed v and the diameter of the cloud of particles at time t is $D(t) = D_0 + 2vt$. In this model the total number of particles in the cloud is

$$N = \left(\frac{D_0}{d} \right)^3. \quad (8)$$

Let F_0 represent the total light intensity flux from the original asteroid. *i.e.* from an asteroid with cross-sectional area $A_0 = \pi D_0^2/4$. Thus, in an ‘aperture’ of diameter $D_{aperture} > D_0$ the total flux is F_0 at time $t = 0$.

The expanding dust cloud is optically thick while the cross-sectional area of all the particles ($A_{particles} = N a_{particle} = N \pi d^2/4$) is greater than the cross-sectional area of the cloud ($A_{cloud} = \pi D^2/4$). Thus, the time until which the cloud is optically thick is given by

$$N d^2 \geq (D_0 + 2v t_{thick})^2 \quad (9)$$

or

$$t_{thick} = \frac{1}{2v} \left(\sqrt{\frac{D_0^3}{d}} - D_0 \right) \quad (10)$$

$$\sim \frac{1}{2v} \sqrt{\frac{D_0^3}{d}} \quad (11)$$

since $D_0 \gg d$.

Our canonical disruption of a 100 m diameter asteroid into micron-sized particles (10^{-6} m) in a cloud expanding at 1 m/s remains optically thick for about $t_{thick} \sim 6$ d after which it is about 1,000 km in diameter. Our nominal photometry aperture $\theta_{aperture} = 3''$ corresponds to about $D_{aperture} = \theta \Delta \sim 3,300$ km at a geocentric distance of $\Delta = 1.5$ au

typical of main belt asteroids so the cloud begins to thin before it reaches the aperture diameter. The time at which the cloud fills the aperture is given by

$$t_{aperture} = \frac{\theta \Delta}{2v} \quad (12)$$

and for most cases $t_{thick} < t_{aperture}$. In our nominal situation $t_{aperture} \sim 1.65 \times 10^6 \text{ s} \sim 19 \text{ d}$

For $t \leq t_{thick}$ the flux in the aperture relative to the initial flux increases like the cross-sectional area of the dust cloud:

$$f(t) = \frac{F(t)}{F_0} = \left[\frac{D(t)}{D_0} \right]^2 = \left(\frac{D_0 + 2vt}{D_0} \right)^2 = \left(1 + \frac{2vt}{D_0} \right)^2. \quad (13)$$

We use a small f to represent the flux relative to the initial flux. In our nominal case $2vt \gg D_0$ so that

$$f(t) \sim \left(\frac{2vt}{D_0} \right)^2. \quad (14)$$

For $t_{thick} < t \leq t_{aperture}$ the flux in the aperture relative to the initial flux remains constant because, even though the cloud is optically thin, all the light is still contained in the aperture:

$$f(t) = N \frac{\pi d^2/4}{\pi D_0^2/4} = \left(\frac{D_0}{d} \right)^3 \frac{d^2}{D_0^2} = \frac{D_0}{d}. \quad (15)$$

Our nominal case yields a 10^8 increase in brightness of the object corresponding to $\Delta V = 20!$

Once $t > t_{aperture}$ the dust is optically thin and the flux in the aperture is only contributed by the dust *within* the aperture. The ‘aperture’ is a ‘cylindrical hole’ through a sphere where the cylinder has a diameter $D_{aperture}$ with spherically shaped ends (see fig. 10). We assume that the dust is homogeneously distributed in the cloud so that the number of particles in the aperture is $n(t) = N V_{aperture}(t)/V_{cloud}(t)$ where $V_{aperture}(t)$ and $V_{cloud}(t) = \frac{4}{3}\pi[D(t)/2]^3$ are the volumes of the aperture and the entire cloud respectively. Letting $r_a = D_{aperture}/2$ and $R(t) = D(t)/2$ but omitting the time dependence for clarity:

$$V_{aperture} = V_{cylinder}(r_a, R) + 2 V_{cap}(r_a, R) \quad (16)$$

$$= 2\pi r^2 \sqrt{R^2 - r^2} + \frac{1}{3}\pi \left(R - \sqrt{R^2 - r^2} \right) \left(\left(R - \sqrt{R^2 - r^2} \right)^2 + 3r^2 \right) \quad (17)$$

For $t > t_{aperture}$ the flux in the aperture relative to the initial flux is simply the ratio of the cross-sectional area of the particles in the aperture to the cross-sectional area of the original asteroid. Computing the ratio and substituting $R(t) \simeq vt$:

$$f(t) = \frac{n(t) a_{particle}}{\pi (D_0/2)^2} \quad (18)$$

$$= n(t) \left(\frac{d}{D_0} \right)^2 \quad (19)$$

$$= N \frac{V_{aperture}(t)}{V_{cloud}(t)} \left(\frac{d}{D_0} \right)^2 \quad (20)$$

$$= \frac{D_0}{d} \frac{V_{aperture}(t)}{V_{cloud}(t)} \quad (21)$$

$$= \frac{D_0}{d} \left[1 - \frac{(t^2 v^2 - r^2)^{3/2}}{t^3 v^3} \right]. \quad (22)$$

To summarize the time behavior of the flux relative to the original flux:

$$f(t) = \begin{cases} \frac{(D_0 + 2vt)^2}{D_0^2} \sim \frac{4v^2}{D_0^2} t^2 & 0 < t < t_{thick} \\ \frac{D_0}{d} & t_{thick} < t \leq t_{aperture} \\ \frac{D_0}{d} \left[1 - \frac{(t^2 v^2 - r_a^2)^{3/2}}{t^3 v^3} \right] & t > t_{aperture} \end{cases} \quad (23)$$

The change in magnitude in the photometry aperture is $\Delta m(t) = -2.5 \log_{10} f(t)$:

$$\Delta m(t) = \begin{cases} -2.5 \log_{10} \left[\frac{4v^2}{D_0^2} t^2 \right] & 0 < t < t_{thick} \\ -2.5 \log_{10} \left[\frac{D_0}{d} \right] & t_{thick} < t \leq t_{aperture} \\ -2.5 \log_{10} \left[\frac{D_0}{d} \left[1 - \frac{(t^2 v^2 - r_a^2)^{3/2}}{t^3 v^3} \right] \right] & t > t_{aperture} \end{cases} \quad (24)$$

Thus, in our model the magnitude decreases (gets brighter) like $\log t$ for $t < t_{thick}$, remains constant for $t_{thick} < t < t_{aperture}$ and finally increases (gets fainter) like $\log t$ for $t \gg t_{aperture}$.

The rate of change in magnitude in the photometry aperture is

$$\frac{d\Delta m(t)}{dt} = \frac{2.5}{\ln(10)f(t)} \frac{df(t)}{dt} \quad (25)$$

so that

$$\frac{d\Delta m(t)}{dt} = \begin{cases} -\frac{5}{\ln 10} \frac{1}{t} \sim -\frac{2}{t} & 0 < t < t_{thick} \\ 0 & t_{thick} < t \leq t_{aperture} \\ -\frac{3 \frac{2.5}{\ln(10)} r^2 \sqrt{t^2 v^2 - r^2}}{t(t^2 v^2 \sqrt{t^2 v^2 - r^2} - r^2 \sqrt{t^2 v^2 - r^2} - t^3 v^3)} & t > t_{aperture} \\ +\frac{2.5}{\ln 10} \frac{2}{t} \sim +\frac{2}{t} & t \gg t_{aperture} \end{cases} \quad (26)$$

Thus, 200 d after the catastrophic disruption the apparent magnitude in the photometry aperture is increasing at a rate of $\sim 0.01 \text{ mag d}^{-1}$. Figs. 2 and 3 show the behavior of the change in brightness and rate of change in brightness using our example disruption and a range of particle expansion velocities. We find that for our 453-day survey window and a reasonable range of expansion velocities, the magnitude decay rate spends most of its time between 0.01 and 0.1 mag d⁻¹.

Table 1. P1010ae Observational Parameters

Parameter	Value
(R.A., declination) (J2000)	(21 ^h 22 ^m 39 ^s , −19°48′12″)
Ecliptic longitude & latitude w.r.t. Opposition	(0.5°, −2.0°)
Rate of motion	0.24 deg day ^{−1}
<code>digest2</code> scores ¹	MB1 = 42, MB2 = 39, MB3 = 5
Great-circle residual	0.02″
Absolute <i>V</i> -magnitude ²	16.5
Heliocentric distance ²	1.95 AU

¹See §2.4.

²From the maximum likelihood orbit computed by OpenOrb (Granvik *et al.* 2009). The orbit and digest score were computed using only the first two detections of the three-detection tracklet because the third detection was contaminated by an electronic artifact.

Table 2. Recent ‘activated’ Solar System objects

Object	Type	Diameter (km)	Period of activity	Nature of activity	Δm (mag)	τ (m day ⁻¹)
P/2010 A2 ¹	MBC*	0.12	2009-2011	Collision	< 19	0.055
P/2010 A2 ¹	MBC*	0.12	2009-2011	Rotational breakup	3.9	0.014
(596) Scheila ²	MBA [†]	113	2010	Crater formation	1	0.03
17P/Holmes ³	Comet	N/A	2007-2008	Sublimation(?)	15	0.04
P/2012 F5 (Gibbs) ⁴	MBC*	2.0	2011-2012	Crater formation	2.0	0.002
P/2013 P5 ⁵	MBC*	0.24	Apr.-Sep. 2013	Episodic rotational	N/A	N/A
P/2013 R3 ⁶	MBC*	Multiple ⁷	Sep.-Dec. 2013	Rotational breakup	4.0	0.03

*Main belt comet (Hsieh and Jewitt 2006)

[†]Main belt asteroid

¹Computed using the upper limit of Δm from Jewitt (2012) over a 9-month interval.

²Bodewits *et al.* (2011)

³Stevenson and Jewitt (2012)

⁴Novakovic *et al.* (2014), Stevenson *et al.* (2012)

⁵Jewitt *et al.* (2013). The effect of multiple, possibly layered, episodes of regolith release for P/2013 P5 preclude a meaningful notion for brightness increase Δm or decay τ .

⁶Jewitt *et al.* (2014)

⁷P/2013 R3 was discovered already split into at least 10 fragments, with the largest having an effective diameter $\lesssim 400$ m. We crudely estimated Δm using brightness decay measured by Jewitt *et al.* (2014) extrapolated to an average disruption date between February and September 2013.

Table 3. Estimated number of catastrophic disruptions per year brighter than $V = 18.5$ that will be detected by ongoing and anticipated asteroid surveys.

Survey	Dates of Operation	Survey Efficiency*	Mag Range	Disruptions/Year
Pan-STARRS1	2010-2013	0.4	13-22	0.8
Pan-STARRS1	2014	0.9	13-22	2
Pan-STARRS1+2	2015-2016	1	13-22	2
Catalina Sky Survey	2014-	1	13-22	2
ATLAS	2016-2018	2	6-20	10
SST [†]	2015(?)-	2	13-22	4
LSST	2021(?)-	2	18-24.5	0 [‡]

[†]Estimated from Shah *et al.* (2013).

[‡]The LSST will have a saturation limit of $V \sim 18$ (Kantor 2013) ensuring that nearly zero $V < 18.5$ disruptions will be detected.

*Our measure of a survey’s ability to detect catastrophic disruptions near opposition over a single lunation. Efficiency > 1 indicates repeat visits to the same region over successive lunations.

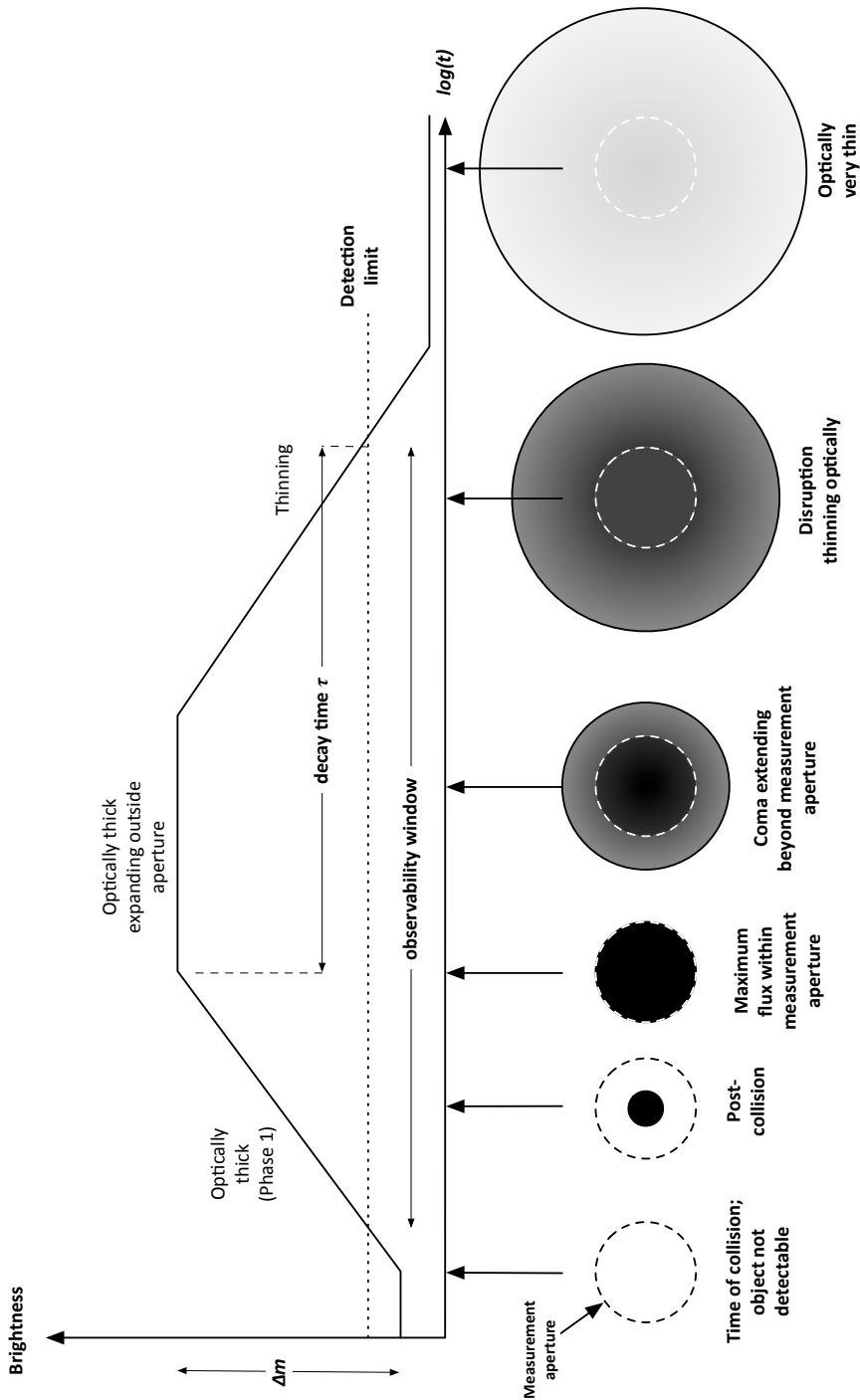


Fig. 1.— Our model (bottom) of a catastrophic disruption and its associated photometric behavior in a small fixed aperture (top). For this example the disruption plateau occurs when the dust cloud is optically thick while expanding beyond the measurement aperture. A plateau can also occur if the dust cloud is thinning but is completely enclosed by our measurement aperture. Our model is discussed in detail in §2.1.

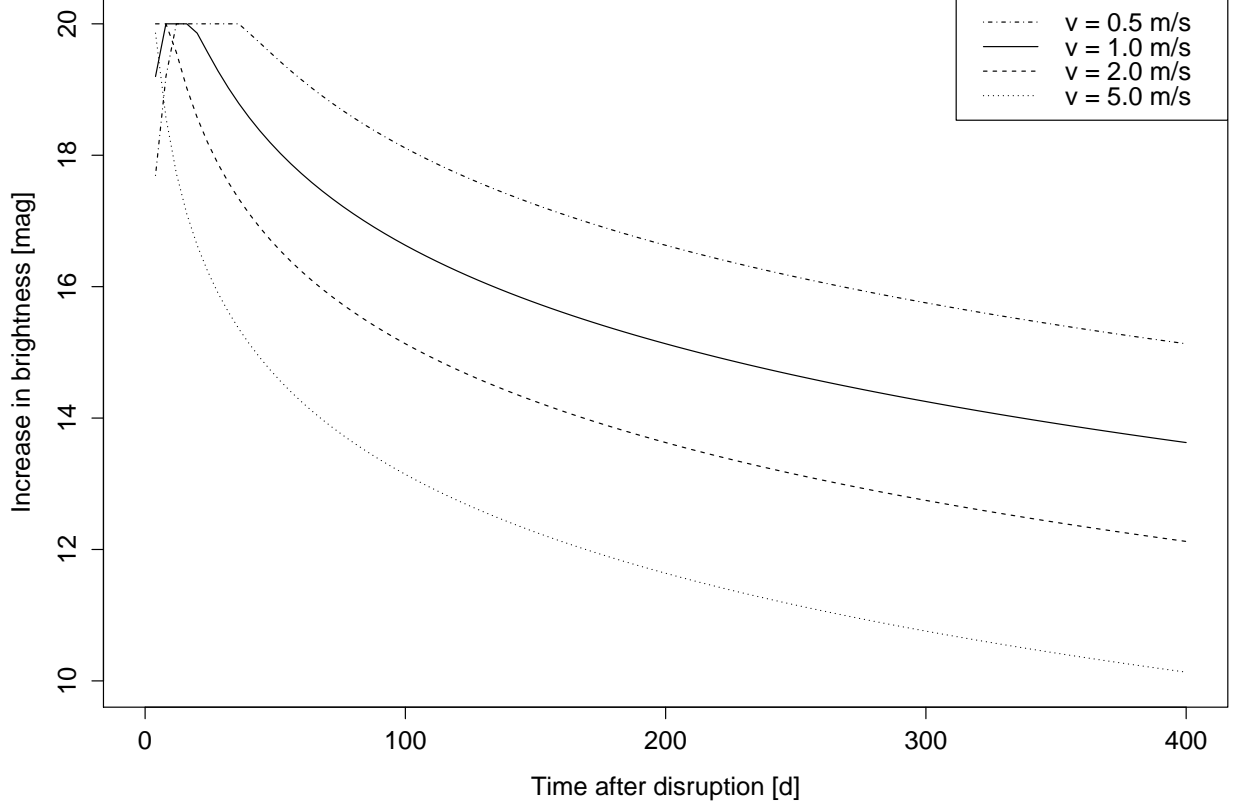


Fig. 2.— The increase in brightness of a model catastrophic disruption for a range of dust dispersion velocities. Our nominal case of a 100 m parent body converted to $1\ \mu\text{m}$ particles results in a +20 increase in magnitude. In all cases, a sharp increase in brightness occurs, followed by a brief plateau, then a decay in brightness. While the magnitude profiles are not linear, a sawtooth profile (instant rise in brightness followed by linear decay) captures the essential behavior for simulation purposes.

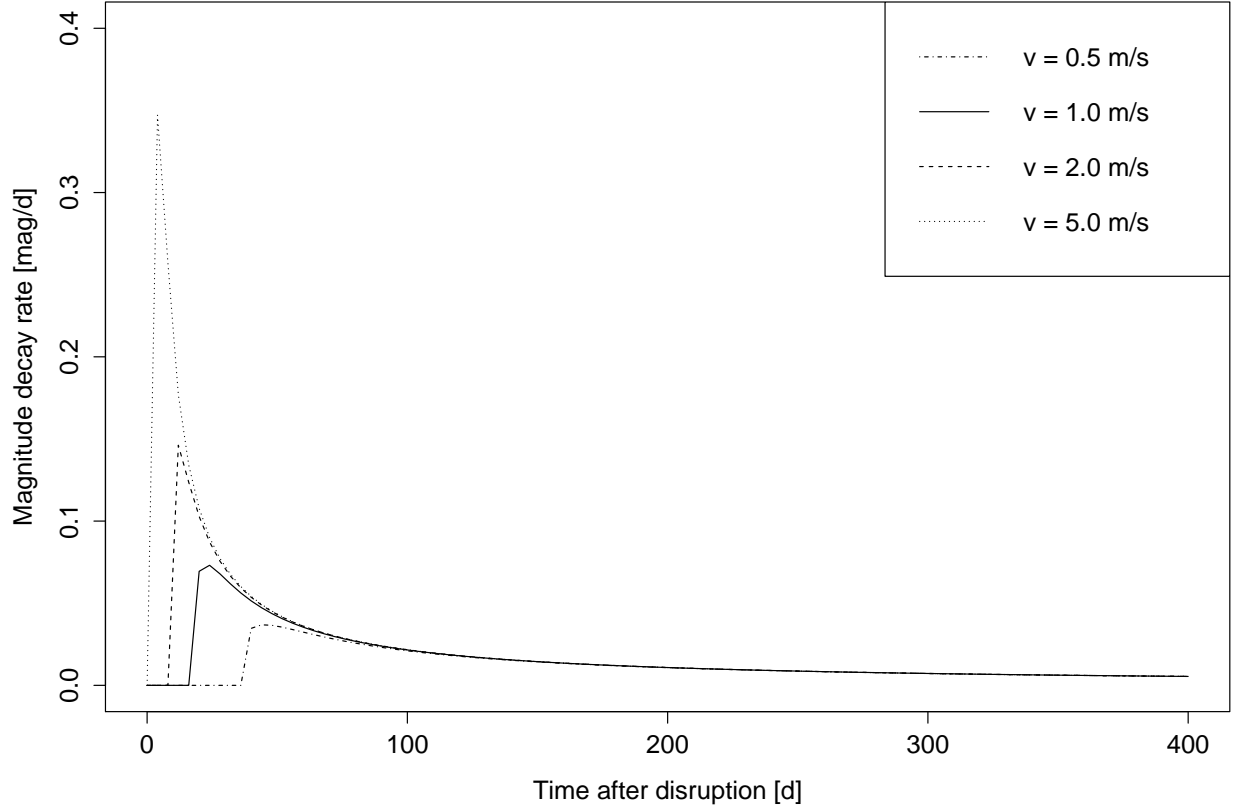


Fig. 3.— Time derivatives for the brightness profiles of fig. 2. Except for rapid initial decay of large (*e.g.* 5 m s^{-1}) dust dispersion velocities, all our model disruptions exhibit brightness decays from ~ 0.1 to 0.01 mag d^{-1} .

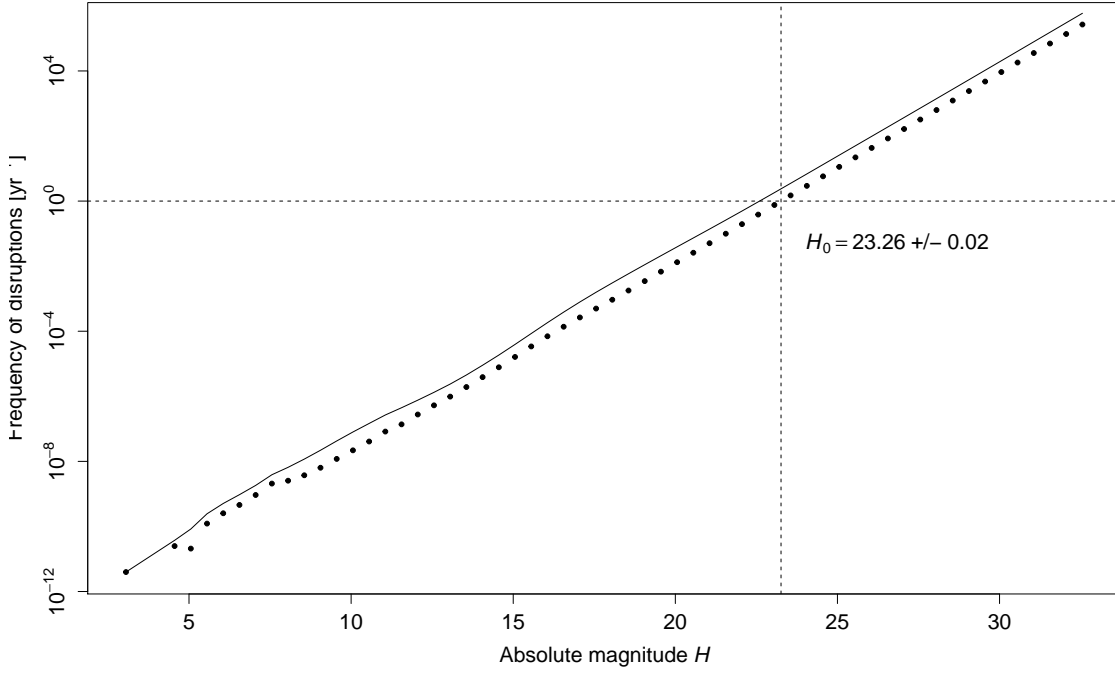


Fig. 4.— Catastrophic main belt asteroid disruption event frequency as a function of absolute magnitude H from Bottke *et al.* (2005). The black dots represent the interval in each absolute magnitude bin. The solid line represents the cumulative disruption interval for asteroids larger than a given absolute magnitude. Our fit to the model yields a power-law slope of $\beta = 0.57 \pm 0.002$ and suggests that one ~ 100 m diameter main belt object is catastrophically disrupted each year corresponding to $H_0 = 23.26 \pm 0.02$.

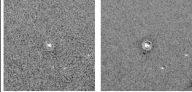
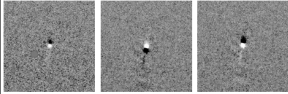
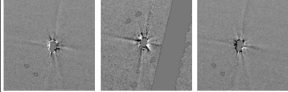
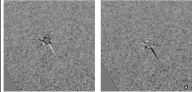
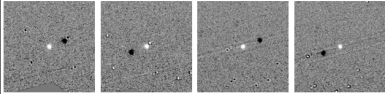
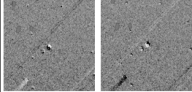
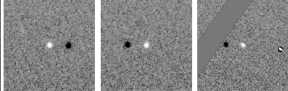
Name	V Magnitude	Stamps	
P102lXu 2012-02-15T05:21:39.OZ	17.32 V		Subtraction artifact
P101wGO 2011-10-13T05:33:48.OZ	17.67 V		Camera artifact
P102Msn 2012-02-24T13:38:35.OZ	18.14 V		Subtraction artifact
P102Tn0 2012-03-11T08:42:42.OZ	18.32 V		Subtraction artifact
P100LFU 2011-07-19T09:05:38.OZ	18.38 V		KNOWN OBJECT 2011 NJ ₁
P1033db 2012-03-28T15:18:27.OZ	18.41 V		Subtraction artifact
P1010ae 2011-08-09T09:38:39.OZ	18.46 V		CANDIDATE DISRUPTION V ~ 18.4

Fig. 5.— 200×200 pixel ‘postage stamps’ of pairwise-subtracted images for Pan-STARRS1 tracklets in the MPC’s ‘one night stand’ file in order of increasing magnitude. The brightest unknown real object, P1010ae, has apparent magnitude $V \sim 18.5$. The solid grey areas represent detector gaps or masked pixels.

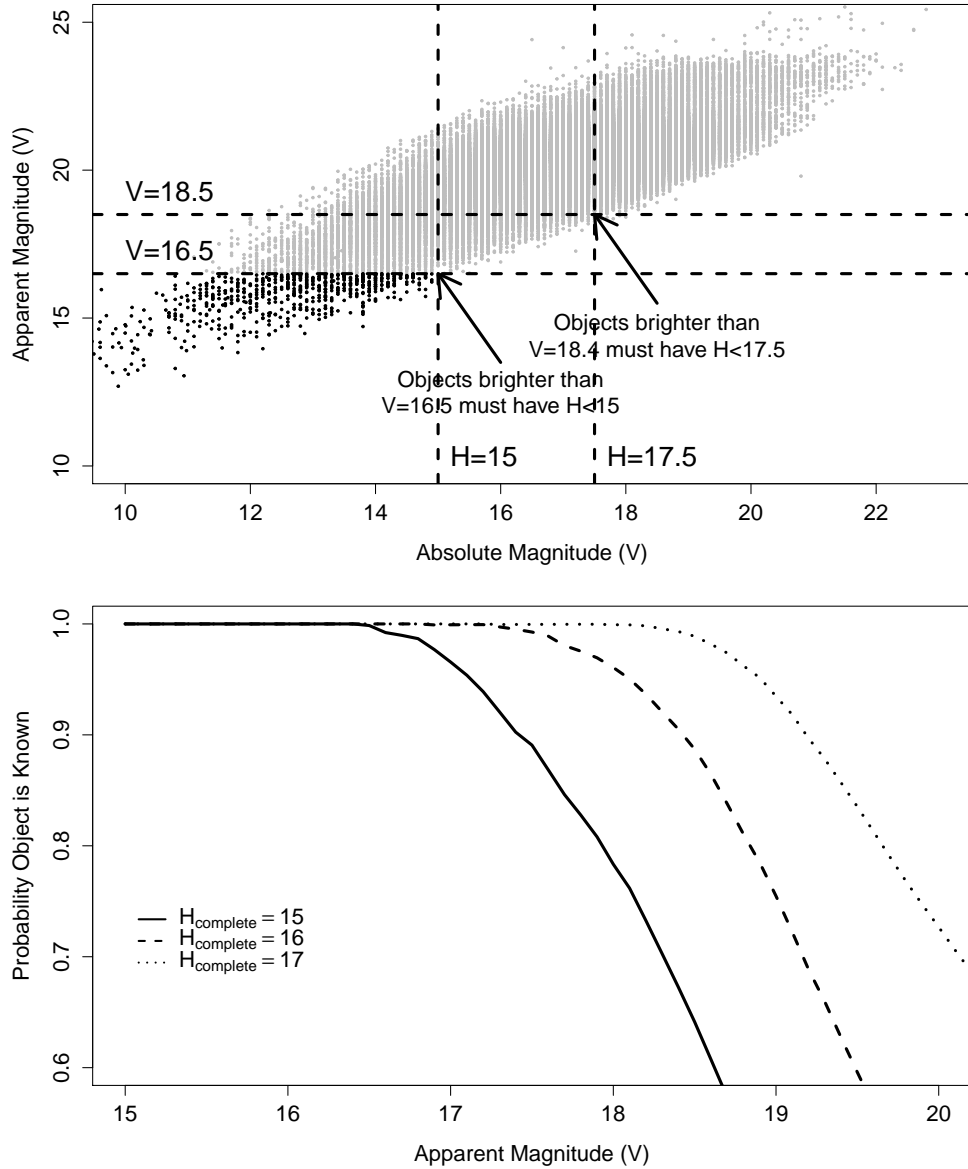


Fig. 6.— (Top) Apparent V magnitude vs. absolute V magnitude of all known main belt asteroids within 30° of opposition on 1 December 2013. The horizontal $V = 16.5$ line corresponds to the faintest magnitude for the sample if the belt is complete to $H = 15$. (Bottom) The probability a tracklet observed near opposition with main belt motion and a given apparent magnitude has $H < H_{\text{complete}}$ for $H_{\text{complete}} = 15, 16$, and 17. Pan-STARRS1 has submitted no unknown tracklets brighter than $V = 18.5$.

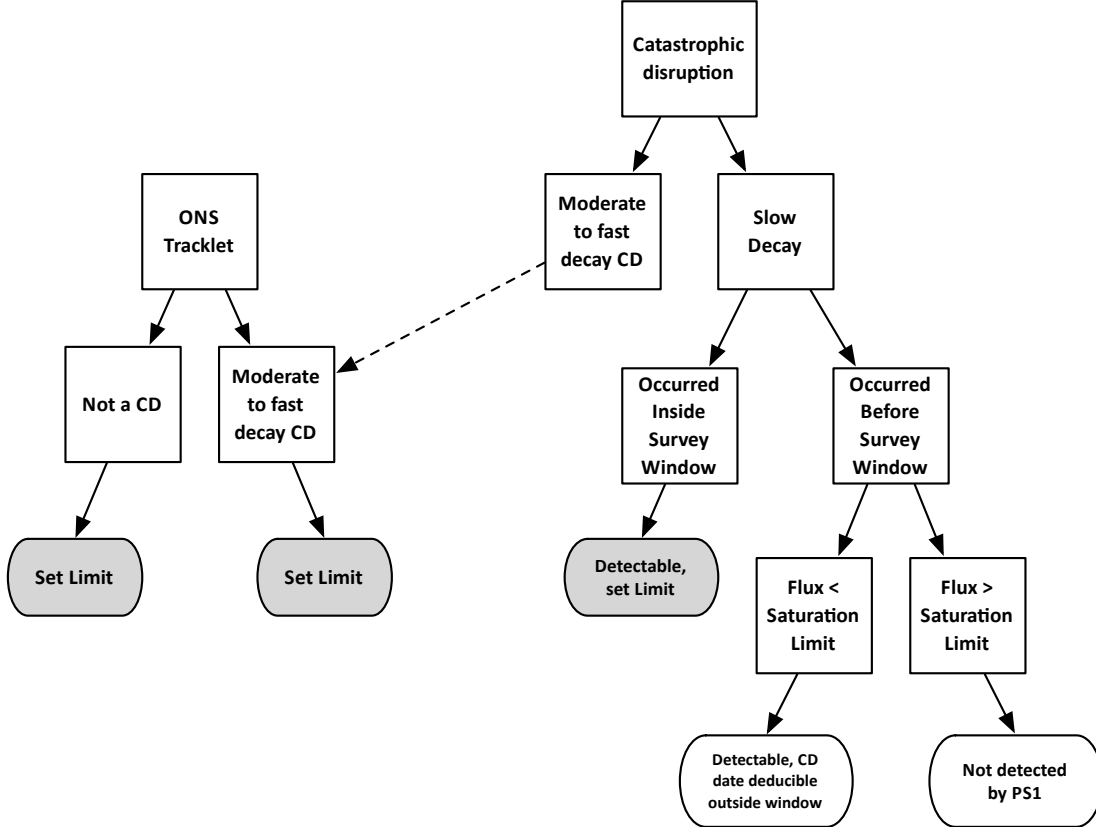


Fig. 7.— The outcome tree that determines the route by which a catastrophic disruption can be detected by the Pan-STARRS1 system and determine a limit. Our one-night-stand (ONS) search is limited to moderate- or fast-decaying catastrophic disruptions. We reason that slower-decaying disruptions in opposition brighter than our $V = 18.5$ brightest candidate limit would have bypassed the ONS process and have been detectable by morphology, as happened with P/2013 P5 and P/2013 R3, which were ~ 2 magnitudes fainter at discovery.

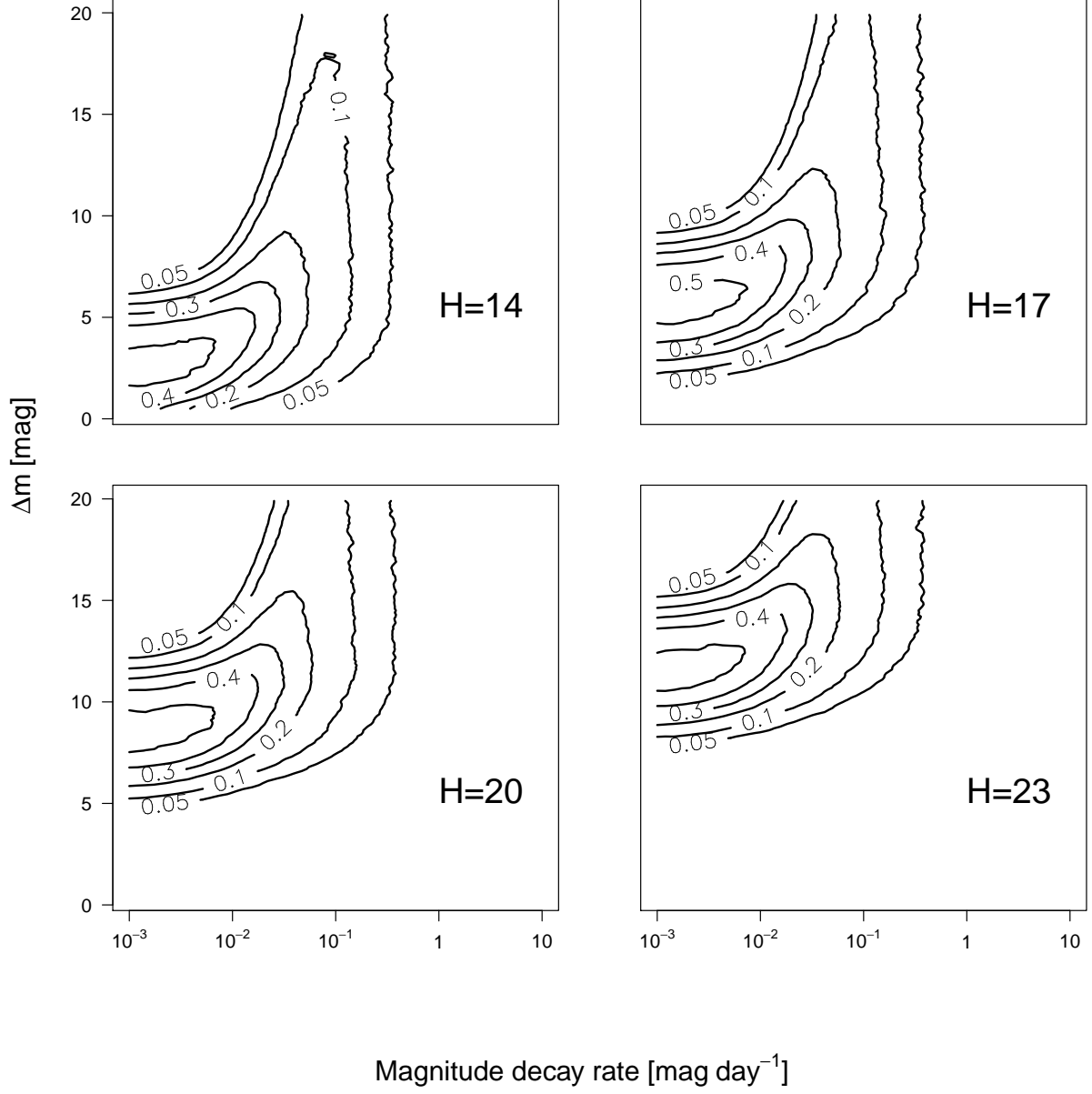


Fig. 8.— Detection efficiency contours at $H = 14, 17, 20$ and 23 for catastrophic disruptions as a function of the brightness increase Δm and magnitude decay rate τ for Pan-STARRS1 pointings over the period 2011-02-21 through 2012-05-19.

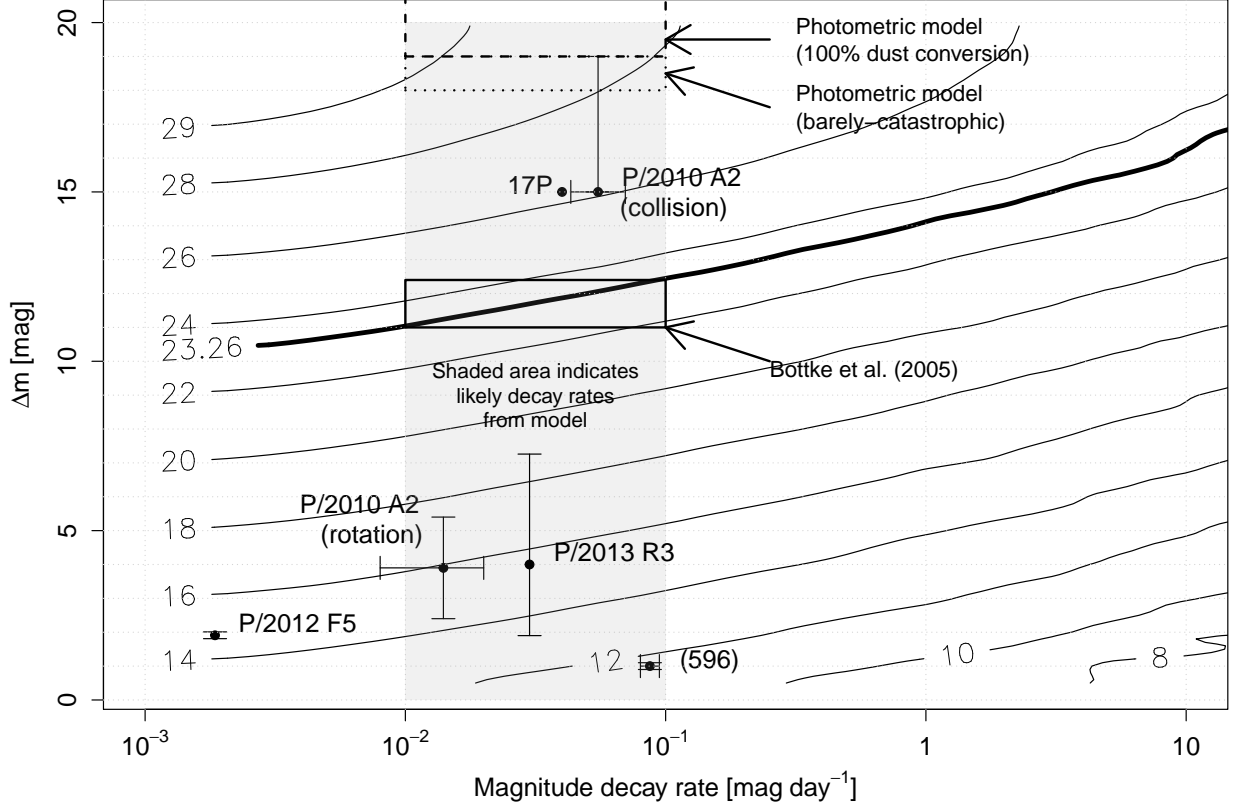


Fig. 9.— 90% confidence limit contours for the absolute magnitude H_0 at which one catastrophic main belt asteroid disruption occurs per year. The grey shaded area indicates the range of magnitude decay rates (τ) we are likely to observe based on our photometric model. The thick solid line corresponds to $H_0 = H_{0,Bottke} = 23.26$ (Bottke *et al.* 2005). The union of this line and our decay limits of 10^{-2} and 10^{-1} form a rectangle that bounds the brightness increase Δm and decay rate τ for catastrophic disruptions if $H_0 = 23.26$ is assumed. The dashed rectangle indicates brightness and decay behavior suggested by our simple collisional disruption model. The discrepancy between these two regions suggests that either that $H_{0,Bottke}$ is incorrect, or that bodies of absolute magnitude $H_{0,Bottke} = 23.26$ (100 m) are disrupting in a way that produces much more modest magnitude increases, *e.g.* +11 to +13 magnitudes, than predicted by our simple model.

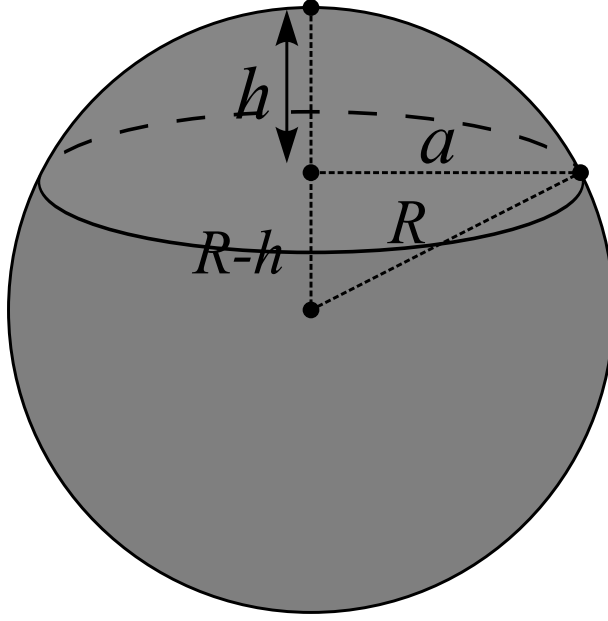


Fig. 10.— Schematic of spherical cap figure to illustrate visible dust cross-section of catastrophic disruption (Weisstein 2014). The volume of the cap is $V_{cap} = \frac{\pi h}{6}(3a^2 + h^2)$. The total contribution of dust seen by a fixed measurement aperture consists of the particles contained in two end caps and the cylinder connecting them.

REFERENCES

- Agarwal, J., D. Jewitt, and H. Weaver 2013. Dynamics of Large Fragments in the Tail of Active Asteroid P/2010 A2. *ApJ* **769**, 46.
- Bodewits, D., M. S. Kelley, J.-Y. Li, W. B. Landsman, S. Besse, and M. F. A’Hearn 2011. Collisional Excavation of Asteroid (596) Scheila. *ApJ* **733**, L3.
- Bottke, W. F., D. D. Durda, D. Nesvorný, R. Jedicke, A. Morbidelli, D. Vokrouhlický, and H. F. Levison 2005. Linking the collisional history of the main asteroid belt to its dynamical excitation and depletion. *Icarus* **179**, 63–94.
- Bottke, W. F., D. Vokrouhlick, D. P. Rubincam, and D. Nesvorný 2006. The yarkovsky and yorp effects: Implications for asteroid dynamics. *Annual Review of Earth and Planetary Sciences* *34*(1), 157–191.
- Chapman, C. R., W. J. Merline, P. C. Thomas, J. Joseph, A. F. Cheng, and N. Izenberg 2002. Impact History of Eros: Craters and Boulders. *Icarus* **155**, 104–118.
- Cikota, S., J. L. Ortiz, A. Cikota, N. Morales, and G. Tancredi 2014. A photometric search for active Main Belt asteroids. *ArXiv e-prints*.
- Davis, D. R., S. J. Weidenschilling, P. Farinella, P. Paolicchi, and R. P. Binzel 1989. Asteroid collisional history - Effects on sizes and spins. In R. P. Binzel, T. Gehrels, and M. S. Matthews (Eds.), *Asteroids II*, pp. 805–826.
- Denneau, L., R. Jedicke, T. Grav, M. Granvik, J. Kubica, A. Milani, P. Vereš, R. Wainscoat, D. Chang, F. Pierfederici, N. Kaiser, K. C. Chambers, J. N. Heasley, E. A. Magnier, P. A. Price, J. Myers, J. Kleyna, H. Hsieh, D. Farnocchia, C. Waters, W. H. Sweeney, D. Green, B. Bolin, W. S. Burgett, J. S. Morgan, J. L. Tonry, K. W. Hodapp, S. Chastel, S. Chesley, A. Fitzsimmons, M. Holman, T. Spahr, D. Tholen,

- G. V. Williams, S. Abe, J. D. Armstrong, T. H. Bressi, R. Holmes, T. Lister, R. S. McMillan, M. Micheli, E. V. Ryan, W. H. Ryan, and J. V. Scotti 2013. The Pan-STARRS Moving Object Processing System. *PASP* **125**, 357–395.
- Dohnanyi, J. S. 1969. Collisional Model of Asteroids and Their Debris. *J. Geophys. Res.* **74**, 2531.
- Dohnanyi, J. S. 1971. Fragmentation and Distribution of Asteroids. *NASA Special Publication* **267**, 263.
- Durda, D. D., R. Greenberg, and R. Jedicke 1998. A New Interpretation of the Size Distribution of Main-Belt Asteroids. In *Lunar and Planetary Institute Science Conference Abstracts*, Volume 29 of *Lunar and Planetary Institute Science Conference Abstracts*, pp. 1680.
- Farinella, P., D. Vokrouhlický, and W. K. Hartmann 1998. Meteorite Delivery via Yarkovsky Orbital Drift. *Icarus* **132**, 378–387.
- Fink, U., and M. Rubin 2012. The calculation of $Af\rho$ and mass loss rate for comets. *Icarus* **221**, 721–734.
- Finson, M. J., and R. F. Probstein 1968. A theory of dust comets. I. Model and equations. *ApJ* **154**, 327–352.
- Gladman, B. J., D. R. Davis, C. Neese, R. Jedicke, G. Williams, J. J. Kavelaars, J. Petit, H. Scholl, M. Holman, B. Warrington, G. Esquerdo, and P. Tricarico 2009. On the asteroid belt’s orbital and size distribution. *Icarus* **202**, 104–118.
- Granvik, M., J. Virtanen, D. Oszkiewicz, and K. Muinonen 2009. OpenOrb: Open-source asteroid orbit computation software including statistical ranging. *Meteoritics and Planetary Science* **44**, 1853–1861.

- Grav, T., R. Jedicke, L. Denneau, S. Chesley, M. J. Holman, and T. B. Spahr 2011. The Pan-STARRS Synthetic Solar System Model: A Tool for Testing and Efficiency Determination of the Moving Object Processing System. *PASP* **123**, 423–447.
- Greenberg, R., W. K. Hartmann, C. R. Chapman, and J. F. Wacker 1978. Planetesimals to planets - Numerical simulation of collisional evolution. *Icarus* **35**, 1–26.
- Harris, A. W. 1996. The Rotation Rates of Very Small Asteroids: Evidence for 'Rubble Pile' Structure. In *Lunar and Planetary Science Conference*, Volume 27 of *Lunar and Planetary Science Conference*, pp. 493.
- Hodapp, K. W., N. Kaiser, H. Aussel, W. Burgett, K. C. Chambers, M. Chun, T. Dombek, A. Douglas, D. Hafner, J. Heasley, J. Hoblitt, C. Hude, S. Isani, R. Jedicke, D. Jewitt, U. Laux, G. A. Luppino, R. Lupton, M. Maberry, E. Magnier, E. Mannery, D. Monet, J. Morgan, P. Onaka, P. Price, A. Ryan, W. Siegmund, I. Szapudi, J. Tonry, R. Wainscoat, and M. Waterson 2004. Design of the Pan-STARRS telescopes. *Astronomische Nachrichten* **325**, 636–642.
- Hsieh, H. H. 2009. The Hawaii trails project: comet-hunting in the main asteroid belt. *A&A* **505**, 1297–1310.
- Hsieh, H. H., and D. Jewitt 2006. A Population of Comets in the Main Asteroid Belt. *Science* **312**, 561–563.
- Ishiguro, M., H. Hanayama, S. Hasegawa, Y. Sarugaku, J.-i. Watanabe, H. Fujiwara, H. Terada, H. H. Hsieh, J. J. Vaubaillon, N. Kawai, K. Yanagisawa, D. Kuroda, T. Miyaji, H. Fukushima, K. Ohta, H. Hamanowa, J. Kim, J. Pyo, and A. M. Nakamura 2011. Observational Evidence for an Impact on the Main-belt Asteroid (596) Scheila. *ApJ* **740**, L11.

- Jacobson, S. A., F. Marzari, A. Rossi, D. J. Scheeres, and D. R. Davis 2014. Effect of rotational disruption on the size-frequency distribution of the Main Belt asteroid population. *MNRAS* **439**, L95–L99.
- Jedicke, R. 1996. Detection of Near Earth Asteroids Based Upon Their Rates of Motion. *AJ* **111**, 970–+.
- Jedicke, R., J. Larsen, and T. Spahr 2002. Observational Selection Effects in Asteroid Surveys. *Asteroids III*, 71–87.
- Jewitt, D. 2009. The Active Centaurs. *AJ* **137**, 4296–4312.
- Jewitt, D. 2012. The Active Asteroids. *AJ* **143**, 66.
- Jewitt, D., J. Agarwal, J. Li, H. Weaver, M. Mutchler, and S. Larson 2014. Disintegrating Asteroid P/2013 R3. *ApJ* **784**, L8.
- Jewitt, D., J. Agarwal, H. Weaver, M. Mutchler, and S. Larson 2013. The Extraordinary Multi-tailed Main-belt Comet P/2013 P5. *ApJ* **778**, L21.
- Jewitt, D., H. Weaver, J. Agarwal, M. Mutchler, and M. Drahus 2010. Newly Disrupted Main Belt Asteroid P/2010 A2. *ArXiv e-prints*.
- Jewitt, D., H. Weaver, M. Mutchler, S. Larson, and J. Agarwal 2011. Hubble Space Telescope Observations of Main-belt Comet (596) Scheila. *ApJ* **733**, L4.
- Kaiser, N. 2004. Pan-STARRS: a wide-field optical survey telescope array. In J. M. Oschmann, Jr. (Ed.), *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Volume 5489 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pp. 11–22.

- Kaiser, N., H. Aussel, B. E. Burke, H. Boesgaard, K. Chambers, M. R. Chun, J. N. Heasley, K.-W. Hodapp, B. Hunt, R. Jedicke, D. Jewitt, R. Kudritzki, G. A. Luppino, M. Maberry, E. Magnier, D. G. Monet, P. M. Onaka, A. J. Pickles, P. H. H. Rhoads, T. Simon, A. Szalay, I. Szapudi, D. J. Tholen, J. L. Tonry, M. Waterson, and J. Wick 2002. Pan-STARRS: A Large Synoptic Survey Telescope Array. In J. A. Tyson and S. Wolff (Eds.), *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Volume 4836 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pp. 154–164.
- Kantor, J. 2013. personal communication.
- Kubica, J., L. Denneau, T. Grav, J. Heasley, R. Jedicke, J. Masiero, A. Milani, A. Moore, D. Tholen, and R. J. Wainscoat 2007. Efficient intra- and inter-night linking of asteroid detections using kd-trees. *Icarus* **189**, 151–168.
- Larson, S. 2007. Current NEO surveys. In G. B. Valsecchi and D. Vokrouhlický (Eds.), *IAU Symposium*, Volume 236 of *IAU Symposium*, pp. 323–328.
- Larson, S., J. Brownlee, C. Hergenrother, and T. Spahr 1998. The Catalina Sky Survey for NEOs. In *Bulletin of the American Astronomical Society*, Volume 30 of *Bulletin of the American Astronomical Society*, pp. 1037.
- Magnier, E. 2006. The Pan-STARRS PS1 Image Processing Pipeline. In *The Advanced Maui Optical and Space Surveillance Technologies Conference*.
- Michel, P., P. Tanga, W. Benz, and D. C. Richardson 2002. Formation of Asteroid Families by Catastrophic Disruption: Simulations with Fragmentation and Gravitational Reaccumulation. *Icarus* **160**, 10–23.
- Milani, A., Z. Knežević, D. Farnocchia, F. Bernardi, R. Jedicke, L. Denneau, R. J.

- Wainscoat, W. Burgett, T. Grav, N. Kaiser, E. Magnier, and P. A. Price 2012. Identification of known objects in Solar System surveys. *Icarus* **220**, 114–123.
- Milani, A., and Z. Knezevic 1994. Asteroid proper elements and the dynamical structure of the asteroid main belt. *Icarus* **107**, 219–254.
- Muironen, K., J. Virtanen, M. Granvik, and T. Laakso 2006. Asteroid orbits using phase-space volumes of variation. *MNRAS* **368**, 809–818.
- Novakovic, B., H. H. Hsieh, A. Cellino, M. Micheli, and M. Pedani 2014. Discovery of a young asteroid cluster associated with P/2012 F5 (Gibbs). *ArXiv e-prints*.
- O’Brien, D. P. 2009. The Yarkovsky effect is not responsible for small crater depletion on Eros and Itokawa. *Icarus* **203**, 112–118.
- O’Brien, D. P., and R. Greenberg 2003. Steady-state size distributions for collisional populations: analytical solution with size-dependent strength. *Icarus* **164**, 334–345.
- Parker, A., Ž. Ivezić, M. Jurić, R. Lupton, M. D. Sekora, and A. Kowalski 2008. The size distributions of asteroid families in the SDSS Moving Object Catalog 4. *Icarus* **198**, 138–155.
- Pravec, P., A. W. Harris, P. Kušnirák, A. Galád, and K. Hornoch 2012. Absolute magnitudes of asteroids and a revision of asteroid albedo estimates from WISE thermal observations. *Icarus* **221**, 365–387.
- Reach, W. T., J. Vaubaillon, C. M. Lisse, M. Holloway, and J. Rho 2010. Explosion of Comet 17P/Holmes as revealed by the Spitzer Space Telescope. *Icarus* **208**, 276–292.
- Sánchez, P., and D. J. Scheeres 2013. The Strength of Regolith and Rubble Pile Asteroids. *ArXiv e-prints*.

- Scheeres, D. J., and P. Sanchez 2012. The Strength of Rubble Pile Asteroids. *AGU Fall Meeting Abstracts*, A5.
- Shah, R., D. F. Woods, W. Faccenda, J. Johnson, R. Lambour, E. C. Pearce, and J. S. Stuart 2013. "asteroid detection with the space surveillance telescope". In *AMOS Conference Technical Papers*.
- Snodgrass, C., C. Tubiana, J.-B. Vincent, H. Sierks, S. Hviid, R. Moissi, H. Boehnhardt, C. Barbieri, D. Koschny, P. Lamy, H. Rickman, R. Rodrigo, B. Carry, S. C. Lowry, R. J. M. Laird, P. R. Weissman, A. Fitzsimmons, S. Marchi, and OSIRIS Team 2010. A collision in 2009 as the origin of the debris trail of asteroid P/2010A2. *Nature* **467**, 814–816.
- Stevenson, R., and D. Jewitt 2012. Near-nucleus Photometry of Outbursting Comet 17P/Holmes. *AJ* **144**, 138.
- Stevenson, R., E. A. Kramer, J. M. Bauer, J. R. Masiero, and A. K. Mainzer 2012. Characterization of Active Main Belt Object P/2012 F5 (Gibbs): A Possible Impacted Asteroid. *ApJ* **759**, 142.
- Tonry, J. L. 2011. An Early Warning System for Asteroid Impact. *PASP* **123**, 58–73.
- Tsuchiyama, A., M. Uesugi, T. Matsushima, T. Michikami, T. Kadono, T. Nakamura, K. Uesugi, T. Nakano, S. A. Sandford, R. Noguchi, T. Matsumoto, J. Matsuno, T. Nagano, Y. Imai, A. Takeuchi, Y. Suzuki, T. Ogami, J. Katagiri, M. Ebihara, T. R. Ireland, F. Kitajima, K. Nagao, H. Naraoka, T. Noguchi, R. Okazaki, H. Yurimoto, M. E. Zolensky, T. Mukai, M. Abe, T. Yada, A. Fujimura, M. Yoshikawa, and J. Kawaguchi 2011. Three-Dimensional Structure of Hayabusa Samples: Origin and Evolution of Itokawa Regolith. *Science* **333**, 1125–.

- Virtanen, J., K. Muinonen, and E. Bowell 2001. Statistical Ranging of Asteroid Orbits. *Icarus* **154**, 412–431.
- Walsh, K. J., P. Michel, and D. C. Richardson 2009. Collisional and Rotational Disruption of Asteroids. *ArXiv e-prints*.
- Weisstein, E. W. 2014. Spherical Cap From MathWorld: A Wolfram Web Resource.
- Willman, M., R. Jedicke, N. Moskovitz, D. Nesvorný, D. Vokrouhlický, and T. Mothé-Diniz 2010. Using the youngest asteroid clusters to constrain the space weathering and gardening rate on S-complex asteroids. *Icarus* **208**, 758–772.
- Zappala, V., A. Cellino, P. Farinella, and Z. Knezevic 1990. Asteroid families. I - Identification by hierarchical clustering and reliability assessment. *AJ* **100**, 2030–2046.